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EXAMINING FACTORS THAT CAN IMPACT CONCEPTUAL LEARNING IN FIRST-YEAR CEGEP CHEMISTRY

by

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DEDICATION

to Leônia, Jafé, Perry, Sandra, and the memory of Marcia

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SUMMARY

Knowledge consists of interrelated concepts that encompass truths, information, and principles that enable a person to construct meaning about the world in a unique way. Learning is a complex, cumulative process by which students add new pieces of information by interpreting them from the vantage point of their preexisting ideas and beliefs. Addressing students' misconceptions in science courses at all levels of instruction has become a major concern for science educators since incomplete, faulty concepts are major hurdles for attaining future effective learning. This exploratory study has multiple goals: It aims to identify misconceptions in chemistry held by first-semester CEGEP students, to investigate how instruction can influence their conceptual learning, and to analyze if gender and language of instruction in high school are significant predictors of conceptual gains.

To identify misconceptions in chemistry and investigate how instruction can influence conceptual learning, 332 first-semester CEGEP Science students in an Anglophone college in Montreal (male:female ratio = 0.83) who were divided in 11 cohorts took the Chemistry Concept Inventory (CCI), a well-researched instrument that contains 22 multiple-choice conceptual questions that test students' knowledge about basic high-school level material. The CCI was administered twice: as a pretest (before receiving instruction) to detect misconceptions brought from high school and as a posttest (after instruction) to provide information about the changes resulting from instruction. The case-study design involved a treatment group and 10 control groups, which were taught the same material by different instructors. The independent variable was the learning activity, which is either a series of computer simulations that provided visualization of chemical phenomena to students (the treatment), or traditional lecture format for the delivery of the material (the control). The treatment involved three computer simulations that were carried out by groups of students in class. These simulations are available on the website of the Phet Interactive Simulations from the University of Colorado at Boulder.

Hake normalized learning gain, based on the differences between pre- and posttest scores, was calculated for each student and for each cohort. The mean of this gain for the whole sample was 6.1%, and the treatment group had the highest gain, 12.1%. The pretest score is a significant predictor ($R^2_{adjusted} = 0.562$, $F(7,324) = 61.73$, $p < 0.01$) of posttest score, which indicates that students who

already knew chemistry concepts at the beginning of the course did better than those holding multiple misconceptions. No statistically significant difference was observed between test scores and the language of instruction in high school. Although neither the cohort nor the treatment was a significant predictor of posttest scores, the results indicate a gender gap in which the treatment is significant for males ($R^2_{adjusted} = 0.497$, $F(5,145) = 30.65$, $p = 0.00685$) but not significant for females. This means that males benefit from the treatment significantly more than females do. One-way ANOVA showed gender as a significant predictor of scores in most of the items in both pretest (14 of 22 questions, $F(1, 330) = 5.19$, $MSE = 0.25$, $p < 0.024$) and posttest (19 of 22 questions, $F(1, 330) = 8.42$, $MSE = 0.25$, $p < 0.004$) with males outperforming females. The combined data indicate the existence of a gender gap in introductory college chemistry, a feature that was not reported in previous studies with the CCI.

The comparison between the misconceptions held by first-year CEGEP students with those reported for American first-year undergraduates enabled the identification of the most challenging concepts for which measured learning gains were either negligible or not observed. This study indicates that concepts dealing with the microscopic scale and size of atoms, the distinction between the physical and chemical properties of aggregate matter compared to the properties of its molecular constituents, as well as the energy changes in the formation and breaking of chemical bonds are among the most challenging concepts detected with the CCI. The results emphasize the difficulties faced by learners related to the triplet representation in chemistry whose understanding requires the distinction between the particulate model used to describe matter, the understanding of chemical and physical properties displayed in laboratory experiments, and the symbolic representations used to describe phenomena. The trends reported extensively for American undergraduate students regarding the types of identified misconceptions and the magnitude of the normalized learning gains align with those found in this study, which indicates the validity of the CCI as a tool to analyze conceptual learning under the specific characteristics of Quebec's CEGEP system.

The crafting of lesson plans that engage learners in the transfer of key concepts and ideas to new settings is paramount to helping them learn chemistry more effectively by selecting an appropriate model in each specific context. This study sheds light on critical issues related to curriculum development by attempting to map the conceptual landscape of first-year CEGEP students and by analyzing the effect of instruction in learning gains. The indication that classroom practices based on computer simulations might be beneficial for enhancing conceptual learning deserves further investigation. The findings of this study can be used to guide fruitful pedagogical discussions among chemistry teachers who are interested in aligning students' pre-knowledge, instruction, curriculum, and assessment.

RÉSUMÉ

Les connaissances d'un être humain sont constituées de concepts interreliés comprenant des vérités, de l'information, et des principes, qui, en somme, permettent à une personne de se construire une réalité unique du monde qui les entoure. L'apprentissage est un processus complexe et cumulatif par lequel les élèves ajoutent de nouvelles informations à leurs connaissances, en les interprétant du point de vue de leurs idées et croyances préexistantes. Aborder les idées fausses que tiennent les étudiants en sciences est devenu une préoccupation majeure pour les enseignants, car des concepts incomplets et défectueux se présentent comme obstacles majeurs à l'apprentissage futur. Cette étude exploratoire a plusieurs objectifs: elle vise à identifier les idées fausses en chimie que tiennent les étudiants du cégep à leur premier semestre, à étudier comment l'enseignement peut influencer leur apprentissage conceptuel, et à analyser si le sexe et la langue d'enseignement au secondaire sont des prédicteurs significatifs des gains conceptuels.

Afin d'identifier les idées fausses en chimie, et dans le but d'étudier de quelle façon l'enseignement peut influencer l'apprentissage conceptuel, 332 étudiants, répartis dans 11 cohortes (ratio hommes/femmes = 0,83), et tous en première année dans le programme sciences de la nature à un cégep anglophone à Montréal, ont complété l'inventaire des concepts de chimie (ICC). Ceci est un instrument bien documenté et fiable, qui contient 22 questions conceptuelles à choix multiples qui mettent à l'épreuve les connaissances des élèves sur de la matière de base, c'est-à-dire de niveau secondaire. L'ICC a été administrée deux fois : en pré-test (avant de recevoir un enseignement sur la matière) afin de repérer les principaux idées fausses transmis par l'école secondaire, et en post-test (après avoir reçu un enseignement sur la matière) dans le but de fournir des informations sur les changements à la suite de l'instruction sur la matière. La recherche était sous forme d'étude de cas, et comprenait 11 groupes différents, dont un seul groupe de traitement et 10 groupes de contrôle, qui ont tous appris le même contenu, mais enseignée par de différents professeurs. La variable indépendante était l'activité d'apprentissage, qui était soit une série de simulations informatiques permettant aux étudiants de visualiser de multiples phénomènes chimiques (le groupe de traitement), ou bien un cours magistral pour présenter le contenu (le groupe de contrôle). Le traitement comportait trois simulations informatiques réalisées par des groupes d'élèves durant la classe.

Ces simulations sont disponibles sur le site web de Phet Interactive Simulations de l'Université du Colorado à Boulder.

Le gain normalisé d'apprentissage de Hake, basé sur l'écart entre les scores pré- et post-test, a été calculé pour chaque élève et pour chaque cohorte. La moyenne de ce gain pour l'ensemble de l'échantillon était de 6,1 % et le groupe de traitement est celui qui a eu le gain le plus élevé, soit de 12,1 %. Le score pré-test est un prédicteur significatif ($R^2_{corrigé}$ = 0,562, F (7,324) = 61,73, p < 0,01) du score post-test, ce qui démontre le fait que les étudiants connaissant déjà les concepts de chimie en question au début du cours réussissent mieux que ceux ayant plusieurs idées fausses. Aucune différence statistiquement significative n'a été observée entre les résultats aux tests et la langue d'enseignement au secondaire. Bien que ni la cohorte ni le traitement ne soient des prédicteurs significatifs des scores post-tests, les résultats indiquent le traitement a eu un effet significatif pour les hommes ($R^2_{corrigé}$ = 0,497, F (5,145) = 30,65, p = 0,00685) mais pas pour les femmes. Autrement dit, les hommes ont beaucoup plus bénéficier du traitement que les femmes. L'analyse de variance à un facteur contrôlé a démontré que le sexe était un prédicteur significatif des scores dans la plupart des éléments tant dans le pré-test (14 de 22 questions, F(1, 330) = 5,19, MSE = 0,25, p < 0,024) que dans le post-test (19 de 22 questions, F(1, 330) = 8,42, MSE = 0,25, p < 0,004). Les données combinées indiquent l'existence d'un écart entre les sexes dans le cours d'introduction à la chimie au niveau collégial, une caractéristique qui n'avait pas été rapportée dans les études antérieures faites avec l'ICC.

La comparaison entre les idées fausses des étudiants de première année du cégep et celles des étudiants américains de première année à l'université a permis de déterminer les concepts les plus difficiles pour lesquels les gains d'apprentissage mesurés étaient négligeables ou non observés. Cette étude indique que les notions portant sur l'échelle microscopique et la taille des atomes, la distinction entre les propriétés physiques et chimiques de la matière agrégée par rapport aux propriétés de ses constituants moléculaires, ainsi que les changements d'énergie dans la formation et la rupture des liaisons chimiques, font partie des concepts les plus incompris et difficiles décelés avec l'ICC. Les résultats soulignent les difficultés rencontrées par les étudiants quant à la représentation en triplet en chimie, dont la compréhension nécessite la distinction entre le modèle particulaire utilisé pour décrire la matière, la compréhension des propriétés chimiques et physiques affichées dans les expériences de laboratoire, et les représentations symboliques utilisées pour décrire les phénomènes. Les tendances observées chez les étudiants américains de premier cycle concernant les types d'idées fausses identifiées et l'ampleur des gains d'apprentissage normalisés sont similaires à celles identifiées par cette étude, ce qui indique la validité et la fiabilité de l'ICC comme outil d'analyse d'apprentissage conceptuel dans les classes de chimie au niveau cégep.

La création de plans de cours qui forcent les étudiants à s'engager dans le transfert de concepts et d'idées clés vers de nouveaux cadres est primordiale pour les aider à mieux comprendre la chimie en adoptant un modèle approprié pour chaque contexte spécifique. Cette étude éclaire des enjeux cruciaux liées au développement de cursus en tentant de tracer l'étendue conceptuelle des étudiants de première année du cégep et en analysant les conséquences de l'enseignement sur les gains d'apprentissage. L'indication que des activités en classe basées sur des simulations informatiques peuvent améliorer l'apprentissage conceptuel mérite une étude plus approfondie. Les résultats de cette étude peuvent être utilisés pour guider des discussions pédagogiques bénéfiques entre les enseignants de chimie qui souhaitent aligner les pré-connaissances, l'enseignement, le curriculum et l'évaluation des élèves.

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LIST OF ABBREVIATIONS, INITIALISMS, AND ACRONYMS

AUCC	Association of Universities and Colleges of Canada
CCI	Chemistry Concept Inventory
CEGEP	Collège d'enseignement général et professionnel
FCI	Force Concept Inventory
MELS	Ministère de l'Éducation et de l'Enseignement supérieur
OECD	Organization for Economic Co-operation and Development
STEM	Science, Technology, Engineering and Math
UNESCO	United Nations Educational, Scientific and Cultural Organization

INTRODUCTION

Since its inception in the 1970s with the investigation of learners' pre-conceptions in basic science topics such as force and energy, the research on conceptual change has diversified to become one of the most important branches in the current science education literature. The Force Concept Inventory (FCI) (Hestenes, Wells, & Swackhamer, 1992; Hestenes, 1998) has become a widely used tool to evaluate the effectiveness of instruction in changing students' misconceptions in introductory Physics courses (Caballero, et al., 2012; Hake, 1998; Scott, Gray, & Yates, 2013). The data accumulated during the past four decades has served as the foundation for ground-breaking theories that explain how students construct knowledge in science. Analyzing the roles of both students' and teachers' conceptual frameworks has triggered significant changes that have molded innovative approaches to teaching and learning at all levels of instruction (Bani-Salameh, 2017; Prince, Vigeant, & Nottis, 2012; Taylor, et al., 2017; Von Korff, et al., 2016).

The shift from traditional teacher-centred practices to student-centred pedagogies is a challenging endeavor that requires a deep understanding of the multiple modes of cognition by which the complex conceptual landscape of students' understanding is structured. A crucial step in designing effective learning environments and strategies is the identification of students' preconceptions and the analysis of how instruction can influence their conceptual learning. In the last decade, the research on conceptual change in college Physics courses in Quebec has received a great deal of attention, and a considerable amount of data has been collected. However, the same type of research on college Chemistry courses is still small despite the steady growth of interest in solving this problem as evidenced by the articles published in international journals since the 1980s. To begin the process of addressing this apparent imbalance, this study is designed to validate the highlyresearched Chemistry Concept Inventory (CCI) which identify common Chemistry misconceptions. Specifically, this study compares the CCI results, based on largely American studies, with the local Quebec context and its unique population by examining its use with first-semester students at an Anglophone college in Montreal. The study also aims to shed light on the influence of instructional strategies in conceptual learning and to analyze if gender and language of instruction in high school are significant predictors of conceptual gains.

In the first chapter, the investigative problem is defined and situated within the context of Quebec's CEGEP system. The second chapter outlines the conceptual framework upon which the research is based. It also defines main concepts and reviews relevant research related to conceptual change. The third chapter presents a literature review describing the sources of misconceptions in chemistry and the relation between instructional strategies and conceptual gain. That chapter also outlines the specific research questions that this study sheds light upon. The fourth chapter describes the methodology of the investigation, the target population and sample, and the instruments used for data collection. Procedures regarding data collection and ethical considerations are also laid out. The fifth chapter presents the results including student demographics, the content analysis of concept inventory items, and the results obtained from data analysis in a pre- and posttest design. The sixth chapter explains the research findings and important themes that emerged. The first of this is the similarities of common misconceptions identified for incoming students in both Quebec colleges and undergraduate programs in American universities. The second finding is a gender gap among the incoming CEGEP population on the Chemistry Concept Inventory's posttest gains, where males score higher than females. The sixth chapter also describes the limitations of the study and outlines future research directions including possible use by college teachers to guide curriculum design.

This research project has been extremely valuable for the researcher as a tool to trigger discussion, engagement, and collaboration among the members of the

Vanier College Chemistry Department. The project execution has also provided insights into some of the main challenges of teaching basic underlying concepts and principles to promote conceptual understanding.

CHAPTER ONE: STATEMENT OF THE PROBLEM

Since the last decades of the 20th century, the number of science students in higher education has been dropping significantly worldwide (OECD, 2006). Increasing dropout rates in middle schools have translated into a decline in science literacy with severe repercussions in the job market (Broman, Ekborg, & Johnels, 2011; Potvin & Hasni, 2014). Industrialized countries struggle to staff positions in key sectors that require specific training, such as science education (Logan & Skamp, 2013; Venville, 2008), health (Nair & Webster, 2010), and information technology (Ali & Shubra, 2010; Xue & Larson, 2015). The inability to attract students to science is a serious threat to keeping up with the necessary technological innovations of today's world (AUCC, 2011; UNESCO, 2010).

Traditional teaching approaches are focused on content (Bunce, 2009; Duit & Treagust, 1998; Ramsden, 2003) and envision education as the transfer of pieces of information to "empty-vessel" learners. However, students have prior notions and perceptions (Bretz, 2005) and often bring ideas that are inconsistent with scientific views (Russell & Martin, 2007). In the last few decades, the research in science education has shifted away from traditional, teacher-centered approaches to student-centered pedagogies whose focus is on the learning process (Bodner, 1986; Fosnot & Perry, 2005; Mortimer & Scott, 2003; Quintana, Shin, Norris, & Elliot, 2006; Reif, 2008; Taber, 2000; Weimer, 2002).

Traditionally conceived as a mere collection of facts and skills that need to be acquired, the concept of knowledge in education has evolved to be a set of interrelated concepts—mental categories or abstract notions—that encompass truths, information, and principles that enable a person to construct meaning about the world (Bodner, Gardner, & Briggs, 2005; Wink, 2001). Science is highly conceptual and learning it effectively requires interconnecting complex frameworks of concepts

(Taber, 2005). Under this new paradigm, the role of the teacher is to facilitate a complex cognitive experience by which learners see, interpret, and create meaning (Cracolice, 2005; Krajcik, Slotta, McNeill, & Reiser, 2008; Novak & Gowin, 1984; Ramsden, 2003; Zusho, Pintrich, & Coppola, 2003).

If students' previous knowledge is incomplete, fragmented, or simply wrong, they can form and develop *alternative* conceptions (Talanquer, 2006; Vosniadou, 2012; Weaver, 2009) or misconceptions—ideas that are not consistent with the views currently held by the scientific community. Identifying misconceptions and understanding how learners consolidate new information with their previous knowledge have become central themes in science education research (Coll, France, & Taylor, 2005; diSessa, 2006; diSessa & Sherin, 1998; Naah, 2015; Vilardo, MacKenzie, & Yezierski, 2017; Vosniadou, 2001).

This work aimed to identify misconceptions in chemistry held by first-semester CEGEP students. The results might be used as a guide to design instructional strategies that have the potential to reverse the observed trends in high-school dropout rates (MELS, 2016) and declining interest in STEM programs (AUCC, 2011) in the province. Enhancing the quality of instruction by providing more interactive, engaging, and rewarding lessons is pivotal to achieving a meaningful and successful learning experience (Fink, 2003; Fraser, 2007; Krajcik, Slotta, McNeill, & Reiser, 2008; Weaver, 2009). The success of this approach has the potential to boost the interest in science as well as the number of students pursuing science careers.

CHAPTER TWO: THE CONCEPTUAL FRAMEWORK

1 INTRODUCTION

The conceptual framework that guided this study stems from the works of Jean Piaget on genetic epistemology (Driscoll, 2000; Gardner, 2006), Lev Vygotsky on cultural-historical aspects of learning (Cole & Gajdamaschko, 2007), David Ausubel (1968) on the importance of prior knowledge and several other key theorists (Cobb, 2005; diSessa, 2006; Pintrich, Marx, & Boyle, 1993; Posner, Strike, Hewson, & Gerzog, 1982; Vosniadou, 2001) who outline the mechanisms by which concepts are restructured. This chapter introduces the evolution of the main theories regarding concept change within a historical perspective.

2 CONDITIONS FOR THE OCCURRENCE OF CONCEPTUAL CHANGE

Piaget's seminal work on children's developing understanding was conducted during the last 15 years of his career (Fosnot & Perry, 2005) and became the grassroots framework for studies on conceptual change by shifting the previous view of learning as knowledge acquisition to learning as knowledge construction (Mayer, 1992). Piaget suggested that young children pass through fixed, sequential stages of cognitive development in a timetable that is universal (Driscoll, 2000). The first stage is *sensorimotor* (from birth to 2 years old) where knowledge is acquired through movement and senses. In the *preoperational* period (2 to 7 years old), children become highly egocentric, not being able to see points of view other than their own. They acquire the semiotic function by which they can mentally represent objects and events. In the *concrete operational* stage (7 to 11 years old), they demonstrate logically integrated thought, invent logical-mathematical knowledge that results in operations but cannot think hypothetically (Driscoll, 2000). Most of the thinking required to understand basic scientific concepts such as conservation of mass and energy, the particulate theory of matter, and the carbon cycle have a level of abstraction that is only available in the *formal operational* stage (11 years old onward) (Herron, 1975; Taber & Corrie, 2007), when children start developing the ability to imagine situations that extrapolate current reality. Although Piaget never intended his theory of knowledge development to be a theory of learning and pedagogy (Gardner, 2006; Kafai, 2006), constructivism became the most important thread from Piagetian studies of conceptual change by envisioning learning as an interpretive, recursive, nonlinear building process accessed by active learners through physical and social interactions (Bodner, 1986; Fosnot & Perry, 2005).

Studies published since the 1970s offer a critique of the use of Piaget's ideas in science education. It has been pointed out that the analysis used in Piagetian research is biased because it is "designed to validate existing theory rather than account for children's reasoning" (Scott, Asoko, & Leach, 2007, p. 33). By envisioning cognition in terms of a conceptual process centered in the individual (Cobb, 2005), Piaget's nativist account minimizes the role of cultural and social factors in the child's mental development by claiming that the sequence of stages of cognitive development appears in a fixed sequence, which is culturally invariant (Driscoll, 2000; Gardner, 2006). Vygotsky's ideas that concepts cannot be transmitted simply through language (Carlsen, 2007) shifted the focus away from the Piagetian view of constructing meaning as solely a function of cognitive processes in the individual to include a socio-cultural perspective (Fosnot & Perry, 2005; Scott, Asoko, & Leach, 2007; Shibley Jr., Milakofsky, Bender, & Patterson, 2003). As a result, the process of constructing knowledge is seen to be mediated by interactions between a student and both peers and the teacher acting in the student's zone of proximal development (Abraham, 2008; Criswell & Rushton, 2012). Others of Piaget's contemporaries such as Papert (Kafai, 2006; Papert & Harel, 1991) and Freire (1998) also emphasized the crucial role of the environment by envisioning learning as an interactive process of discovery mediated by social interactions that enable the acquisition and development of cognitive tools (Taber & Corrie, 2007).

In the 1970s, David Ausubel expanded Piaget's framework by emphasizing the importance of prior knowledge to achieve meaningful learning (Scott, Asoko, & Leach, 2007). According to this view, the learner must possess relevant ideas to which new information can be anchored to (Bretz, 2005). Learning is viewed as a process that uses an advanced organizer that enables the gradual refinement of concepts into more complex structures (Cracolice, 2005). Novak and Gowin (1984) use Ausubel's idea of an advanced organizer to develop concept mapping—an instructional strategy widely used to enhance meaningful and deep learning among students (Cheng & Gilbert, 2009).

Posner et al. (1982) combine the ideas of Piaget, Ausubel, and the landmark work of Thomas Kuhn (1970) to underline the similarities between the changes experienced by individual students and the nature of change in scientific paradigms described in the philosophy and history of science (Abraham, 2008; diSessa, 2006; Kalman, 2008; Pintrich, Marx, & Boyle, 1993). One of Piaget's key ideas is equilibration—a process by which new constructs are created when prior knowledge is disequilibrated and drives learners towards more advanced thinking through reequilibration (diSessa, 2006). Posner's model is based on a view of learning as a rational activity where cognitive conflict, based on the Piagetian idea of disequilibrium (Appleton, 2007), is the first step to promoting accommodation—changing or altering existing schemas in light of new information. Students must be dissatisfied with existing ideas, which will then be replaced with new ideas that are intelligible, plausible, and fruitful (Scott, Asoko, & Leach, 2007). The critique by Pintrich et al. (1993) emphasizes that conceptual change depends heavily on motivational and affective variables (Zusho, Pintrich, & Coppola, 2003) to set favorable social aspects and were not properly taken into account in Posner's work.

The current research incorporates the ideas of Piaget, Vygotsky, Ausubel, Posner, and Printich to analyze students' conceptual change. The next section outlines the theories that explain the mechanisms by which learners organize and relate concepts through mental models in chemistry.

3 CONCEPTUAL CHANGE AND MULTIPLE REPRESENTATIONS IN CHEMISTRY

Vygotsky underlines that scientific concepts are special because they stem from formal conceptual structures that do not arise spontaneously in the everyday experience of a child. Learning science "is a process of moving from the linguistically abstract to the concrete, not vice-versa" (Carlsen, 2007, p. 59). Learning chemistry poses other cognitive constraints since there are three distinct types of representations in this field of knowledge (Chandrasegaran, Treagust, & Mocerino, 2009; deJong & Taber, 2007; Gilbert & Treagust, 2009). The first type is phenomenological, which encompasses the representation of material properties either observed in everyday contexts or measured in controlled laboratory experiments. The second type deals with models (Bodner, Gardner, & Briggs, 2005) used to explain a wide variety of chemical phenomena (Scalco, Talanquer, Kiill, & Cordeiro, 2018). These models are highly abstract, often counterintuitive (Harrison & Treagust, 2002), and involve invisible sub-microscopic entities such as molecules, atoms, ions, radicals, and electrons that cannot be visualized in the same way that biologists see invisible cells and their internal organelles through a microscope. The third type is symbolic, which includes visual representations (Halpine, 2008; LaDue, Libarkin, & Thomas, 2015) that are used to depict chemical transformations through chemical equations, the structural formulae of chemical compounds (Taskin & Bernholt, 2014), their spatial arrangement (Hutchison, 2017; Schwartz & Heiser, 2006; Stull, Gainer, Padalkar, & Hegarty, 2016), as well as all the symbols and conventions displayed in figures, diagrams, and charts (Eilam & Gilbert, 2014; Vilardo, MacKenzie, & Yezierski, 2017).

Navigating through the triplet relationship in chemistry requires a level of cognitive sophistication that is way above the stage of intellectual development of high-school learners. According to Baxter-Magolda (1992), the vast majority of first-semester college students hold a dualistic view, or *absolute knowing*, in which knowledge exists in absolute form and it is simply right or wrong. Progressively, they achieve intellectual maturity going through three other stages: *transitional knowing* where knowledge is certain in some areas and uncertain in others; *independent knowing* where knowledge is uncertain, and everyone has their own beliefs and, finally, *contextual knowing* where knowledge is constructed on the base of evidence and context (Felder & Brent, 2004). Knowing chemistry entails the understanding of the limitations and the validity of contextual knowledge which is based on mental models and modeling (Bodner, Gardner, & Briggs, 2005; Coll, 2006; Edwards & Head, 2016; Justi & Gilbert, 2002; Kozma & Russel, 2005; Rapp, 2005). Students begin to know chemistry when they start navigating with confidence among the different types of representations (Levy & Wilensky, 2009) and, based on scientifically accepted models, devise a clear separation between symbolic and phenomenological representations (Floriano, Reiners, Markic, & Avitabile, 2009; Rappoport & Ashkenazi, 2008; Talanquer, 2011; Treagust, Chittleborough, & Mamiala, 2003).

From a historical perspective, the evolution of basic concepts in science illustrates that early scientists developed and held their own misconceptions while making the transition from one flawed conception to its successor (Barke, Hazari, & Yitbarek, 2009; Duit & Treagust, 1998; Harrison & Treagust, 2002). Due to the inherent transitory nature of models, conceptual change is expected to be an integral part of the learning process at all levels of instruction (Claesgens, Scalise, Wilson, & Stacy, 2008; Criswell, 2011; Gobert, et al., 2011). While studying chemistry, learners are constantly grappling with cognitive conflicts (Sevian, Talanquer, Bulte, Stacy, & Claesgens, 2014) whose patterns are often like those faced by scientists throughout history (Justi & Gilbert, 2000). It is imperative to constantly challenge the dualistic view of knowledge held by incoming college students by engaging them in exercises of model-base reasoning designed to connect the multiple types of representation in chemistry (Sjöström & Talanquer, 2014). This pedagogical approach aims to restructure students' pre-instructional conceptual frameworks to facilitate the acquisition of scientific concepts through *conceptual change* (Duit & Treagust, 2003; Karatas, Ünal, Durland, & Bodner, 2013).

The conceptual framework of this work incorporates the ideas of Baxter-Magolda (1992) about the level of intellectual development of college students. The work is also guided by the research on the multiple representations model in chemical education (Gilbert & Treagust, 2009; Talanquer, 2011) and the principles of conceptual change developed in the last decades (diSessa, 2006; diSessa & Sherin, 1998; Naah, 2015; Vosniadou, 2001).

CHAPTER THREE: LITERATURE REVIEW

This chapter compiles the literature findings based on empirical data about the common types and sources of misconceptions in chemistry. By recognizing the patterns of reasoning used, this type of research aims to provide a framework to understand students' learning difficulties and trace them back to the shortcomings in instructional strategies and used materials such as textbooks. The chapter also compiles the literature findings about active, student-centered learning environments being viable alternatives to restructure misconceptions in comparison with the traditional teacher-centered lecture-based approach and its overreliance on algorithmic problem solving.

1 SOURCES OF MISCONCEPTIONS IN CHEMISTRY

The lack of clarity in textbooks has been shown to be a major source of misconceptions (Sanger & Greenbowe, 1999). Justi and Gilbert (2002) compiled a list of textbooks that present chemistry as a mere collection of true or complete facts and of mathematical formulations. According to the authors, characteristics of several distinct models are often merged to explain, for example, atomic structure, bonding, or chemical kinetics without ever discussing the meaning of the word model. This approach has been shown to prevent students from understanding effectively the fundamental role of models in chemistry (Bodner, Gardner, & Briggs, 2005; Coll, 2006; Criswell, 2011; Edwards & Head, 2016; Rapp, 2005). The use of faulty language in textbooks is also linked to students' preference to rationalize chemical reactivity using teleological explanations (Talanquer, 2007) for which chemical entities have purpose or desire like in "atoms *want* to be stable" (Talanquer, 2013).

Visualization can be used as a powerful explanatory tool to clarify scientific concepts by shining light on subtle aspects and details that are difficult to convey using only language (Akaygun & Jones, 2013; Mammino, 2014). The highly abstract character of chemistry requires, for example, associating subtle structural features in 3D representations of molecules with their reactivity patterns. Computational visualizations (Miorelli, Caster, & Eberhart, 2017) and interactive simulations (Geelan & Fan, 2014) have been widely used to help students to navigate among the three levels of representation in chemistry and restructure their misconceptions (Russel & Kozma, 2005). Due to this highly abstract character, computer-generated visual aids can help students develop spatial awareness which helps them conceptualize symbols and formulas, rather than focusing on algorithmic problem solving (Nakiboğlu & Tekin, 2006; Sanger & Greenbowe, 1997; Yezierski & Birk, 2006).

Eilks, Witteck and Pietzner (2009) discuss the shortcomings of approaches that do not use proper visualizations by showing that computer simulations might foster misconceptions of chemical principles, rather than explaining the scientifically accepted chemical concepts behind them, especially when they are constructed without sufficient reflection on the learners' previous knowledge and level of cognition. The authors point out that poorly designed and implemented visualizations might create and propagate misconceptions in the same way that incoherent textbook explanations do.

Kerr and Walz (2007) ask 91 college students in introductory general chemistry course to use computer and internet resources to individually complete four exercises whose purpose was to rectify misconceptions in atmospheric environmental chemistry. The gains in conceptual understanding were measured by a pretest posttest assessment as well as by questions in a comprehensive course final exam. The authors point out that the gains obtained by the internet activities were modest compared to their expectations. They argue that students are often reluctant to change their misconceptions and that the construction of knowledge can be accomplished only through an intensive process. This fact is illustrated by the improvement observed after lectures and small-group discussions took place which underlines the importance of social interactions among peers to consolidate conceptual change. Other studies reinforce the importance of combining carefully designed online activities (Özmen, Demircioğlu, & Demircioğlu, 2009), lectures, and small-group discussions (Benvenuto, 2001; Brooks & Koretsky, 2011; Shaver, 2010; Varma-Nelson & Coppola, 2005) to restructure students' misconceptions and gradually develop understanding in chemistry (Sevian, Talanquer, Bulte, Stacy, & Claesgens, 2014).

2 ALGORITHMIC PROBLEM SOLVING INSTEAD OF CONCEPTUAL UNDERSTANDING

The differences in learning outcomes that result from instructional strategies that emphasize conceptual understanding against those that use problem solving by routine has been extensively reported in the literature (Ausubel, Novak, & Hanesian, 1978; Barouch, 1997; Bodner, 1986; Haláková & Prokša, 2007; Milakofsky & Patterson, 1979; Nicoll, 2001; Novak & Gowin, 1984). Although the distinction between symbolic representation and conceptual knowledge is natural for experts, studies have shown that novices struggle with navigating between distinct levels of representation (Claesgens, Scalise, Wilson, & Stacy, 2008; Taber, 2009). It is far too common to mistake the ideas for the symbols that are used to represent them (Gabel, 2005). Being able to read the symbols has no direct association with understanding the concepts they represent, which often results in an approach to learn based on memorizing isolated pieces of information that are compartmentalized into tidy, demarcated parts without being properly integrated with their previous knowledge (Ausubel, Novak, & Hanesian, 1978; Novak & Gowin, 1984). Talanquer (2012) points out that the distinction between algorithmic and conceptual problems is subtle and is linked to the approaches used by students to solve them.

Nicoll (2001) interviewed 56 undergraduate chemistry majors from novice through senior years to elucidate their misconceptions about chemical bonding. Chi-square analysis indicates that there was no statistically significant difference between the number of first-year students and seniors holding these misconceptions. The author points out that although these students succeed in the educational system by solving algorithmic problems, the misconceptions seem to be resistant to the type of instruction provided. Regardless of students' final grades, fundamental concepts remain meaningless, which hinders their ability to grapple with the material in advanced courses in either chemistry or other scientific disciplines (Barke, Hazari, & Yitbarek, 2009; Reif, 2008).

Claesgens et al. (2008) develop a multidimensional framework to describe a hierarchy of student understanding in chemistry in relation to three basic topics: "matter is made of atoms," "change is associated with the rearrangement of atoms," and "energy is associated with changes that occur." The authors collected qualitative and quantitative data through classroom observation, cognitive task analysis, interviewing, verbal protocol analysis, and the analysis of video and audio recordings. In the qualitative data collection stage, patterns were identified, and answers were grouped to reflect similarities in thinking approaches and strategies. The results shed light on the distinct stages of intellectual development as students progressed through the sequence of chemistry courses. They entered high-school chemistry in lower areas of Level 1 (notions). They eventually approached Level 2 (recognition) after a year of general high-school chemistry and consolidated this stage after one year of university-level general chemistry, with only a few students able to reason in the lower region of Level 3 (formulation). At the end of the organic chemistry course, they reached Level 4 reasoning (construction). This study provides a good conceptual framework to be used in the introductory CEGEP course General Chemistry I (202-NYA) since both courses start with the same three basic topics. If students succeed in mastering these three and restructure their misconceptions (Barke, Hazari, & Yitbarek, 2009), they will likely succeed in higher-level organic-chemistry courses (Duis, 2011).

3 TEACHING AND LEARNING WITH PEER INSTRUCTION

Despite the diversity of models that explain how learners organize concepts (Chi, Slotta, & de Leeuw, 1994; diSessa, 2006; Vosniadou, 2012), studies have suggested that effective mechanisms to promote conceptual change include intentional reflection (Sinatra, 2002), self-explanation (Chi, Slotta, & de Leeuw, 1994), and tasks that involve compare and contrast (Bransford, Brown, & Pellegrino, 2000). Vygotsky's seminal work proposed a theory that saw reasoning as emerging through practical activity in a social environment (DelRio & Álvarez, 2007), an idea that was further developed by showing the importance of learners working together to create an artifact that can be shared with others to gain a deeper conceptual understanding through lively negotiations (Papert & Harel, 1991).

This new paradigm focuses on the learning process and shifts away from traditional views where teachers tend to underestimate the need to learn basic scientific concepts by asking simple questions dealing with simple concepts (Mazur, 2005). In college chemistry courses, many new concepts are introduced at a fast pace, without sufficient time being allocated to interpret and elaborate them in depth. Studies have indicated that providing opportunities to conceptualize symbols and formulas rather than focusing on algorithmic problem solving is a common thread of effective instructional strategies that promote chemistry literacy (Benvenuto, 2001; Özmen, Demircioğlu, & Demircioğlu, 2009; Sanger, 2009; Varma-Nelson & Coppola, 2005).

The importance of socio-interactions among peers in mediating knowledge construction through a process of discovery is the basis of active-learning pedagogies, among which peer instruction (PI) (Mazur, 1997) has become, in the last decade, widely adopted at the post-secondary level. Findings on the current literature of PI underline the gains in conceptual understanding when the course material is organized to promote student participation. Breaking lectures into short segments that are alternated with learning activities that enable students to process information in a realistic and timely manner has been shown to produce gains in conceptual learning (Drane, Micari, & Light, 2014; Freeman, et al., 2014; Parkinson, 2009; Von Korff, et al., 2016).

Empirical evidence (Brooks & Koretsky, 2011; Lyle & Robinson, 2003; McCreary, Golde, & Koeske, 2006) has shown that a successful approach to fostering critical thinking should include a variety of activities in the classroom (individual, small group, and whole class) to promote discussion that leads to the description of concepts and models in a format that includes debate, testing, and application of concepts to new situations. Besides the pre- and posttests administered at the beginning and end of the term, Brooks and Koretsky (2011) used reflective individual written answers to elucidate the changes students undergo in specific in-class PI assignments. For each question, the researchers created a hierarchical code scheme for the type of misconceptions involved. The validity of the codes was determined by comparing specific questions' codes with misconceptions that were previously identified in the literature for the same concept.

The research reviewed here indicates that the common misconceptions can be classified according to patterns of reasoning (Talanquer, 2010) based on students' misunderstanding of chemical principles when they use faulty common sense (Talanquer, 2006). The compiled results also point out that restructuring misconception is a complex task that requires the design of well structured instructional strategies and the use of proper materials (Akaygun & Jones, 2013).

This work has the goal to identify the misconceptions that are held by first-year students taking the introductory General Chemistry course (202-NYA) in an Anglophone CEGEP in Montreal. The proposed investigation also aims to analyze the potential of using instructional strategies based on peer instruction to help students restructure their misconceptions.

4 RESEARCH QUESTIONS

Question #1: What are the main misconceptions about basic principles in chemistry that CEGEP science students bring from their high-school chemistry courses?

This question addresses a philosophical underpinning of studies on misconceptions: the importance of determining students' prior knowledge (Bodner, 1986; Bransford, Brown, & Cocking, 2000; Fosnot & Perry, 2005; Novak & Gowin, 1984; Scott, Asoko, & Leach, 2007). Identifying students' misconceptions and analyzing how they are restructured can also shed light on how these concepts are mentally represented, which is an issue of primary concern in studies in this field (Chi, 1997; Chi, Slotta, & de Leeuw, 1994; Criswell & Rushton, 2012; diSessa & Sherin, 1998; Vosniadou, 2001).

Question #2: Are instructional strategies that foster student interaction more effective than traditional approaches to promote conceptual gains?

Studies have shown that both college and university students can succeed in chemistry courses without mastering basic conceptual knowledge (Duis, 2011; Galley, 2004; Nash, Liotta, & Bravaco, 2000; Nicoll, 2001). These findings can be rationalized by the fact that students' approaches to learning involve mostly memorizing chunks of information and learning to solve problems using algorithms without a conceptual framework. In this research question, this study aims to analyze if instructional strategies that foster student interaction with peers are more effective than traditional lecture-based strategies in restructuring students' misconceptions in introductory CEGEP chemistry courses.

Question #3: What factors play a role in acquiring knowledge in introductory college chemistry courses?

Since acquiring deep conceptual understanding requires a prominent level of proficiency in the language of instruction, this research question is of interest for

Quebec's CEGEP system. Most of students in Anglophone colleges attend French schools and have their first chemistry course taught in English when they start the CEGEP level. Does the language of instruction in pre-college schooling have a significant effect on conceptual understanding achievement in introductory courses taught in an Anglophone CEGEP? Does gender play a role in acquiring knowledge at this level?

Question #4: What is the validity of the CCI with the local population?

By comparing the CCI results obtained in multiple studies conducted with a large sample of first-year American undergraduate students with this study's findings, this investigation can validate the use of the CCI as a tool to analyze conceptual learning under the specific characteristics of Quebec's CEGEP system.

CHAPTER FOUR: METHODOLOGY

1 RESEARCH DESIGN

The research study used a quasi-experimental design involving a case-study of 10 sections of a first-year Chemistry course at the CEGEP level. A summary of the research design and timeline of interventions is shown in Table 1. The case-study design involved a treatment group and 10 control groups, which were taught the same material by different instructors. The independent variable was the learning activity, which is either a series of computer simulations to provide visual aid to students (the treatment), or traditional lecture format for the delivery of the material (the control). The treatment involved three computer simulations available on the website of the Phet Interactive simulations from the University of Colorado at Boulder (https://phet.colorado.edu/). The three selected simulations illustrate important aspects of the particulate nature of matter. *States of Matter* illustrates the principles of the Kinetic Molecular Theory and show how variables such temperature and pressure influence the behavior of gases at the molecular level whereas *The Photoelectric Effect* explores the wave-particle duality of light and an important periodic property—the ionization energy. By comparing multiple atomic models from Dalton to Schrödinger, the third simulation, *Models of the Hydrogen Atom*, offers an opportunity to reflect on the applicability and limitations (Coll, 2006) of each mental model created to portray matter at the atomic level. The handouts given to students are compiled in Appendix A. Asking students to write their own explanations gives them an opportunity to organize their ideas and identify concepts that might conflict with their current views (Weaver, 2009). They worked in pairs for the first half of the class and used the remaining time to discuss their findings with other groups.

Table 1
Research Design and Time Table of Interventions

Week	Intervention
1	Survey of Demographic Data
2	Mulford & Robinson's Chemistry Concept Inventory – Pretest
4	Phet Simulation: States of Matter
6	Phet Simulation: The Photoelectric Effect
8	Phet Simulation: The Models of the Hydrogen Atom
14	Mulford & Robinson's Chemistry Concept Inventory – Posttest

The dependent variable was the comprehension of basic high-school level chemistry concepts. The variable is operationalized by both the overall and individual questions grades as well as the changes in the answers for each individual question in a concept inventory test given at the beginning and at the end of the course. The Chemistry Concept Inventory (CCI) (Mulford & Robinson, 2002) has become a popular tool in education research to detect chemistry misconceptions. It also serves as a measure of the effectiveness of instruction if given to students twice as a pretest (before receiving instruction) and a posttest (after instruction). It consists of 22 multiple-choice conceptual questions that test students' knowledge about basic high-school concepts. Most of the questions have four or five answers with only one being correct whereas the others are different distracters. As observed in other concept inventories, the selection of the distracters is the result of a careful analysis of several reported studies of common students' misconceptions, including frequent test answers, drawings, and interviews (Barke, Hazari, & Yitbarek, 2009; Bretz & Mayo, 2018; Johnson, 2005; Kahveci, 2013; Luxford & Bretz, 2014; Mortimer & Scott, 2003).

2 SAMPLE TARGET AND POPULATION

The target population is the first-year college level students in a public institution in the Montreal area, an English CEGEP. The participants are a convenience sample of science program students enrolled in an introductory chemistry course, namely 202-NYA General Chemistry, from this institution. The Registrar's Office randomly distributed the sample of 332 students across 11 sections taught by distinct instructors.

3 INSTRUMENTS

The two instruments for collecting data in this research are

1. A survey to gather demographic data from participants, namely age, sex, mother tongue, and language of instruction in high school.

2. A concept inventory test used as a diagnostic tool to identify weak areas of understanding of basic concepts in high-school chemistry.

The Chemistry Concept Inventory (**CCI**) is the instrument used in this study. It is a multiple-choice diagnostic tool used to indicate the level of chemistry misconceptions held by students. The inventory is composed of one- and two-tiered non-mathematical conceptual questions (22 questions total). The inventory (Robinson, n.d.) is available from the Chemical Education Xchange website, which was formerly known as the Journal of Chemical Education website. As stated online, this inventory is free for use. In addition, the author gave explicit written permission for its use in this project (W. R. Robinson, personal communication, May 13, 2015). Psychometric analysis (Barbera, 2013; Schwartz & Barbera, 2014) conducted with over 2500 students from four universities confirmed the validity and reliability of the instrument.

4 DATA COLLECTION

The CCI pretest was administered during week 2 of a 15-week course, and the posttest was administered in week 14. No communication was allowed during the 25 minutes that students were given to complete the CCI. Students recorded their answers to the CCI questions directly on an optical scan form. Data from students that did not provide consent were removed from each data set. Students who did not respond all 22 items during both administrations were also removed from the data set. Complete data from 332 students were obtained. After the data was converted to an Excel spreadsheet, it was manually checked to ensure that student answers were correctly represented. In addition to simple mean and standard deviation analysis overall and by demographic category, an analysis of variance (ANOVA), and linear regression were performed to determine the statistical correlation with each category.

5 PROCEDURE AND ETHICAL CONSIDERATIONS

This study was granted permission by the Vanier College Research Ethics Board (see Appendix C). Informed written consent was obtained from all students before administering the pretest concept inventory. All participants were informed that their confidentiality was protected by coding their work. They were informed that they could withdraw from participating at any point. Participants were informed of the nature of the study and that it might be combined with subsequent studies. The consent form can be seen in Appendix B. The research data is being stored in a secure location for a length of time that the ethics committee at Vanier College suggests. The Ethics board deemed the research low risk and determined that there was no need for parental consent for participants less than 18 years of age.

During the first week of class, a third party, a teacher who had not previously taught those students, distributed, explained, and collected the consent forms. They were told that the results of the work may be published anonymously, but only if they had given specific permission for this, wherein their consent would only be known after they had completed the course and their final marks for the course were submitted to the college. The third party kept the consent forms in sealed envelopes. Data analysis only took place after the conclusion of the course when the materials became available to the researcher. Students who did not give consent participated in the course work with the other students, but the data they generated was not used.

CHAPTER FIVE: RESULTS

1 STUDENT DEMOGRAPHICS

A pre-study demographic survey was administered as a measure to gather information about potential dependable variables in the study such as sex, age, mother tongue, and language of instruction in high school. The sample (N=332) has 181 females (54.5%) and 151 males (45.5%), an overall male / female ratio of 0.83. The main group age is 17 years old (73.2%), followed by 16 years old (10.5%) and 18 years old (5.4%). Table 2 displays the overall distribution of both the mother tongue and the language of instruction in high school. Most students (52.7%) are allophones, and only a third have English as their mother tongue. The majority (59.9%) were educated in French whereas 37.6% received high-school instruction in English. Table 3 shows the students' demographics by cohorts.

Table 2
Demographics: Mother Tongue and Language of Instruction
in High School [Fall 2016] (N = 332)

	English	French	Other
Mother tongue	111 (33.4%)	46 (13.8%)	175 (52.7%)
Language of instruction in high school	125 (37.6%)	199 (59.9%)	8 (2.4%)

Table 3
Cohort Composition in Terms of Male/Female Ratio
and Language of Instruction in High School [Fall 2016]

Cohort	N	Male:Female Ratio	Language of instruction in high school		
			English	French	Other
11	33	0.65	42%	58%	0%
12	29	0.93	34%	66%	0%
13	23	2.29	17%	78%	4%
14	19	1.38	26%	68%	5%
15*	**34**	**0.70**	**50%**	**50%**	**0%**
16	34	0.62	38%	59%	3%
17	33	0.74	58%	42%	0%
18	29	0.45	41%	55%	3%
19**	**34**	**0.79**	**38%**	**62%**	**0%**
20	33	0.94	39%	58%	3%
21	31	1.07	16%	74%	10%
overall	332	0.83	38%	60%	2%

* Cohort 15 is the treatment group.
** Cohort 19 is the Honours Science group.

2 CONTENT ANALYSIS OF CONCEPT INVENTORY ITEMS

In the last decade, concept inventories have been developed to target key chemical misconceptions in a variety of topics such as bonding (Luxford & Bretz, 2014), light and heat (Chandragasegaran, Treagust, & Mocerino, 2007), quantum chemistry (Dick-Perez, Luxford, Windus, & Holme, 2016), redox reaction (Brandriet & Bretz, 2014), thermochemistry (Wren & Barbera, 2013), heat and energy (Prince, Vigeant, & Nottis, 2012), the photoelectric effect (Önder, 2016), and flame test (Bretz & Mayo, 2018).

Typical questions in concept inventories assess students' conceptual understanding of basic chemical principles by interacting with symbolic representations used in chemical equations and formulas (Taskin & Bernholt, 2014) as well as the depiction of the particulate model of matter (Bretz & Mayo, 2018).

Schwartz and Barbera (2014) conducted a content analysis of the 22 questions in Mulford and Robinson's (2002) CCI to determine which concepts appeared in the inventory. The results are summarized in Table 4 and elicit that this CCI has two major concepts appearing in multiple items: conservation of mass/matter is covered in six items (1, 4, 7/8, 10/11, 12/13, and 18/19) whereas the concept of phase change is covered in four items (2, 3, 6, and 10). No other concepts were covered in more than three items.

Table 4
Content Analysis for Individual Questions in Mulford and Robinson's Chemistry Concept Inventory (Schwartz & Barbera, 2014)

Concept	Questions
Conservation of Mass-Matter	1, 4, 7/8, 10/11, 12/13, 18/19
Phase Change	2, 3, 6, 10/11
Stoichiometry/Limiting Reagent	1, 5, 18/19
Solutions	15, 20/21
Physical *vs* Chemical Change	2, 6
Specific Heat Capacity; Thermodynamics	16/17
Bond Energy	9
Size of an Atom/Mole; Scale/Estimation/Proportion	14
Macro *vs* Microscopic Properties	22

3 GAIN CALCULATION

There are different forms used to report the learning gains using concept inventories in a pretest versus posttest design. The simplest way is the *raw gain*, which is the difference between the scores in both tests. As an alternative to the raw gain, Hake (1998) proposed the *normalized gain* $\langle g \rangle$, defined in Equation 1, as an accurate way of analyzing growth on the tests even if the groups being compared performed differently on the pretest.

$$\langle g \rangle = \frac{\langle post\% \rangle - \langle pre\% \rangle}{100\% - \langle pre\% \rangle} \tag{1}$$

where $\langle\ \rangle$ indicates average scores.

The denominator in Equation (1) attempts to compensate for issues that are commonly observed in calculations based on simple difference scores, such as ceiling effects and the bias of low absolute gain when pretest scores are high (Mayer K. , 2011; Pentecost & Barbera, 2013).

The *individual normalized gain* is calculated for each individual student, but their average is not the same as the Hake normalized gain because

$$\frac{\sum \frac{post\% - pre\%}{100\% - pre\%}}{n} \neq \frac{\frac{\sum post\%}{n} - \frac{\sum pre\%}{n}}{100\% - \frac{\sum pre\%}{n}} \tag{2}$$

The normalized gain and the individual normalized gain are useful in different circumstances. The former offers a simple parameter to compare separate groups collectively whereas the later is a more appropriate metric to compare trends observed for the individuals in those groups. Table 5 shows both the pre- and posttest averages and the normalized learning gains for the groups in this study.

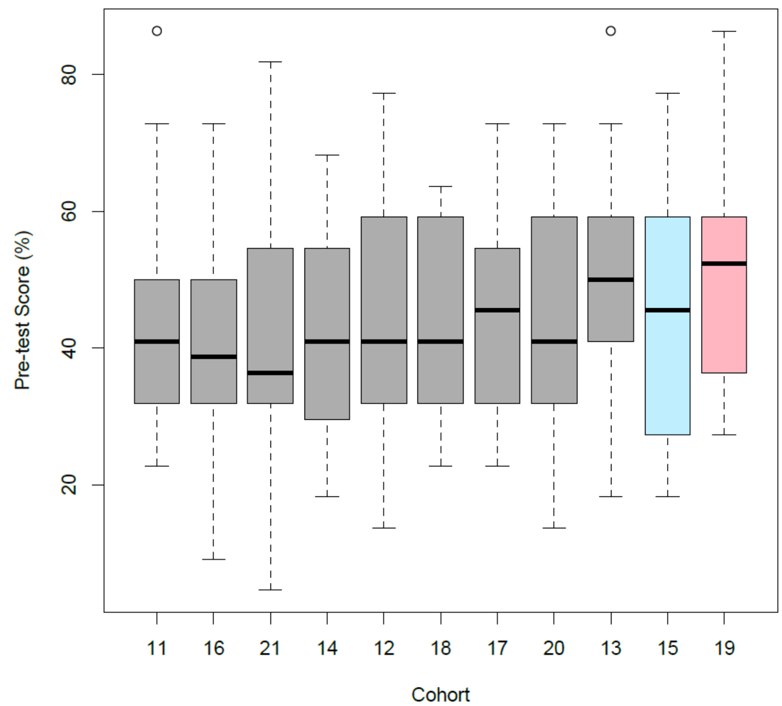
According to the criteria stablished by Hake (1998) for the interpretation of $\langle g \rangle$, all gains in Table 5 would be classified as low since $\langle g \rangle < 0.3$. The treatment group, cohort 15, showed the highest gain (12.1%), followed by cohorts 20 (10.4%) and 16 (9.5%). Figure 1 shows the descriptive measures for all cohorts. However, the differences in normalized gains cannot be attributed exclusively to the instructional strategies employed since the groups cannot be considered equivalent. For example, cohort 19 (Honours Science) showed the highest average scores for both the pretest (51.5%) and posttest (55.5%), whereas the third highest gain (cohort 16, 9.5%) showed the lowest pretest score (39.8%).

Table 5
Pre- and Posttest Averages and the Normalized Gains for All Groups

Cohort	N	Pretest (%)			Posttest (%)			Normalized Gain (%)
		mean	median	std. dev.	mean	median	std. dev.	
11	33	44.4	40.9	15.3	43.9	40.9	19.8	-0.9%
12	29	43.6	40.9	20.3	46.4	40.9	16.5	5.0%
13	23	49.2	50.0	16.6	51.4	54.5	19.1	4.3%
14	19	42.1	40.9	15.3	45.9	45.5	14.8	6.6%
15*	**34**	**45.5**	**45.5**	**17.8**	**52.1**	**54.5**	**21.5**	**12.1%**
16	34	39.8	38.6	15.6	45.5	45.5	13.9	9.5%
17	33	45.7	45.5	14.7	47.8	45.5	18.6	3.9%
18	29	44.7	40.9	14.0	46.6	50.0	18.2	3.4%
19**	**34**	**51.5**	**52.3**	**16.3**	**55.5**	**50.0**	**16.8**	**8.2%**
20	33	43.5	40.9	16.4	49.4	50.0	18.8	10.4%
21	31	42.7	36.4	18.6	45.6	40.9	23.1	5.1%
Overall	**332**	**44.8**	**40.9**	**16.6**	**48.3**	**45.5**	**18.6**	**6.1%**

* Cohort 15 is the treatment group.
** Cohort 19 is the Honours Science group.

These scores for both pretest (44.8%, SD = 16.6) and posttest (48.3%, SD = 18.6) fall in a similar range of those reported by Mulford and Robinson (2002) for a group of 928 first-year American engineering majors with pretest and posttest averages respectively equal to 46.8% (SD = 3.82) and 50.9% (SD = 4.09), with a 7.7% normalized gain. Working with 2392 students enrolled in a first-semester general chemistry course at four different universities in the United States, Pentecost and Barbera (2013) reported an averaged normalized learning gain of 7.0%, with both pre and posttest scores in the range of 40 to 49%.



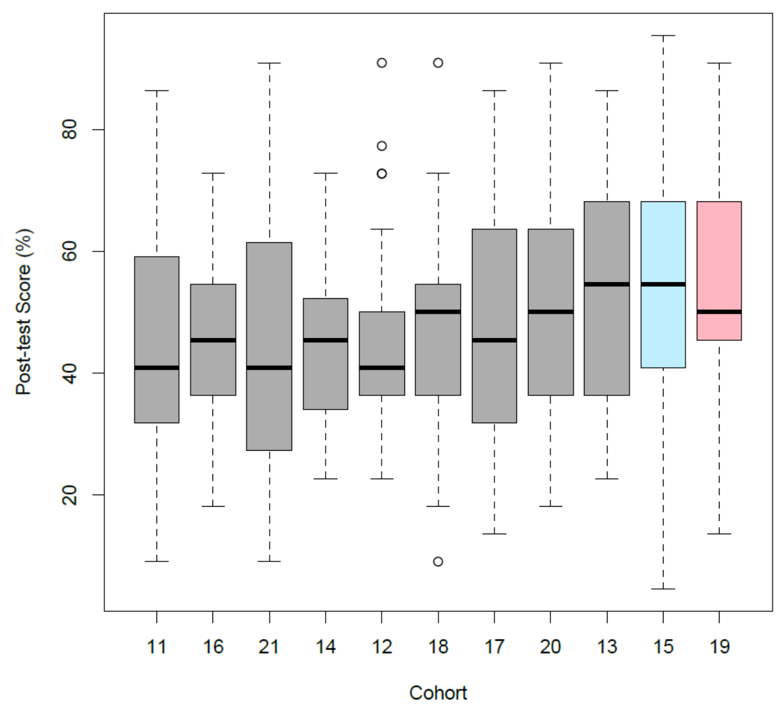


Figure 1 Descriptive Measures for Pre and Posttest for Cohorts. (Treatment: cohort 15; Honours Science: cohort 19)

4 RESULTS FOR INDIVIDUAL QUESTIONS

Questions 7 and 8 deals with the conservation of mass in chemical reactions. This set had the highest overall score in the CCI for both tests: 85% (pre) and 86% (post) answered both questions correctly. Questions 12-13 (both pre and post: 74%) address the same issue in physical transformations and was the second highest overall score of the test. The fundamental concept that mass and matter are conserved in both chemical and physical processes is also present in question 1 (pre: 41%, post: 44%), question 4 (pre: 59%, post: 63%), and questions 10-11 (pre: 36%, post: 43%). As outlined by Mulford and Robinson (2002), the combination of these results indicated that both sets of questions (7-8 and 12-13) may prompt simple recall whereas students struggle to transfer the concept of mass conservation to the concrete situations described in the other questions. The combined results of questions 18 and 19 corroborate this assumption since more than half of the students choose the right justification in question 19 (pre: 54%, post: 58%) but failed to apply the concept within the context of question 18 (pre: 41%, post: 42%) which deals with the formation of rust by the reaction between iron and oxygen.

Question 2 deals with the basic concept that in physical change between states of matter, the chemical identity of the substance, i.e. its chemical composition, is kept. The question asks the chemical composition of the vapors obtained when water is boiled. Less than half of the students chose the right answer (pre: 41%, post: 39%). There was an increase in the number of students assuming that the vapor is made of oxygen gas and hydrogen gas (pre: 39%, post: 44%). A study with 10th graders conducted by Mayer (2011) reported that a demonstration showing that the collected vapor is not flammable produced a noticeable increase in the correct answer (pre: 8%, post: 48%), despite the fact that "oxygen gas and hydrogen gas" still appeared with high frequency (pre: 48%, post: 32%).

In question 6, the same physical change, water evaporation, is portrayed using balls to represent atoms and molecules. The fact that this question states that *evaporated water* was formed, resulted in a substantial increase for the correct answer (pre: 48%, post: 55%). A considerable number of students assumed that that the vapor is made of oxygen atoms and hydrogen atoms (pre: 25%, post: 19%), and a smaller fraction selected the option of oxygen gas and hydrogen gas (pre: 11%, post: 13%).

The low scores observed for question 5 (pre: 13%, post: 19%) reflect a poor understanding of chemical formulas and equations within the context of stoichiometry involving limiting reagent in chemical reactions. These results are in alignment with an independent study (Kruse & Roehrig, 2005) with the same CCI that shows that only 11% of students and 50% of high-school teachers selected the correct answer.

Question 9 (pre: 40%, post: 53%) is the only one covering the concept of bond energy. In this topic, a persistent misconception (Galley, 2004) revolves around the erroneous idea that breaking chemical bonds releases energy while bond making requires energy. This misconception appeared frequently in both pre (45%) and posttest (34%) answers. In the study conducted by Kruse and Roehrig (2005), 30% of teachers believed that breaking H–H and O–O bonds releases energy compared to 72% of their student sample.

The low scores for question 14 (pre: 14%, post: 17%) illustrates the difficulties of dealing with the microscopic scale and size of atoms. The fact that the majority of students (pre: 75%, post: 78%) chose the familiar Avogadro's number (6.02×10^{23}) as the number of carbons atoms in a dot (**.**) indicate the lack of understanding of the concept of mol. Comparable results were reported in Kruse and Roehrig's (2005) study where 33% of high-school teachers and 75% of the student sample chose Avogadro's number as the answer.

Although the introductory college chemistry course does not specifically address concepts in solution chemistry, students' responses indicates a good understanding of the concept of dilution as portrayed in question 15 (pre: 71%, post: 77%). On the other hand, low scores were obtained for questions 20 (pre: 24%, post: 23%) and 21 (pre: 14%, post: 16%) due to lack of understating of the behavior of a saturated solution. Most students (pre: 71%, post: 72%) believed that the concentration of salt in solution goes up when water evaporates. The most prevalent rationale that was chosen in question 21 is that *there is the same amount of salt in less water* (pre: 49%, post: 58%). In Kruse and Roehrig's (2005) study, 30% of the teachers and 64% of students held the same misconception.

Questions 16-17 deals with the topics of thermochemistry and specific heat capacity. Both are covered in high-school and are part of the curriculum of the introductory college chemistry course. Question 16 showed a noticeable gain (pre: 38%, post: 45%) whereas a decrease was observed for question 17 (pre: 40%, post: 35%). The most prevalent misconception for question 16 is the same amount of heat is required to warm equal masses of water and alcohol from 25 °C to 50 °C (pre: 41%, post: 40%). In Kruse and Roehrig's (2005) study, 35% of the teachers and 51% of the students hold this misconception whose source is traced to a widespread confusion between heat and temperature.

The low scores for question 22 (pre: 19%, post: 23%) indicates the difficulty of distinguishing the properties of a macroscopic sample of sulfur from that of a single atom. Most students (pre: 63%, post: 60%) indicated that a single atom of sulfur is a brittle, crystalline solid; with a melting point of 113 °C, and/or had a density of 2.1 g/cm^3. In Kruse and Roehrig's (2005) study, 74% of the teachers and 81% of the students held the same misconception.

5 ANALYSIS OF VARIANCE

One-way ANOVA between groups were used to test if there is a statistically significant difference between them. Correlations between the results of either pre- or posttest were tested for gender and language of instruction in high school. No statistical significant correlation was found for the language of instruction in any question in both tests. However, the effect of gender was significant for several questions in the CCI (14 items in the pretest and 19 items in the posttest) with males outperforming females. The results can be seen in Table 6.

By considering the posttest as an outcome variable and the pretest as one of the input variables, the data was analyzed through regression by

1. Splitting groups by cohort
2. Splitting groups by treatment

The pretest score is a significant predictor ($R^2_{adjusted} = 0.562$, $F(7,324) = 61.73$, $p < 0.01$) of posttest score, which indicates that students who already know chemistry concepts at the beginning of the course tend to do better than those who hold multiple misconceptions (Barbera, 2013). Neither the cohort nor the treatment are significant predictors of posttest score (see Figure 2). However, the results indicate a clear gender gap in posttest scores on the CCI, as shown in Figure 3. The interaction between gender and treatment is significant for males ($R^2_{adjusted} = 0.497$, $F(5,145) = 30.65$, $p = 0.00685$) but not significant for females, which indicates that the treatment affects positively the understanding of male students.

Table 6
Correlation Between Gender and the Answers for Each Question of the CCI.
(n.s. = no statistically significant correlation was observed)

Question	Pretest			Posttest		
	F(1,330)	MSE	p	F(1,330)	MSE	p
1	2.89	0.24	n.s	14.38	0.25	< 0.0002
2	5.62	0.24	< 0.02	11.21	0.24	< 0.001
3	9.69	0.25	< 0.002	20.11	0.25	< 0.0001
4	23.85	0.24	< 0.00001	17.76	0.23	< 0.00003
5	0.92	0.11	n.s.	6.16	0.15	< 0.02
6	8.36	0.25	< 0.005	10.49	0.25	< 0.002
7	8.96	0.13	< 0.003	8.74	0.12	< 0.004
8	13.33	0.16	< 0.0003	10.70	0.12	< 0.001
9	2.44	0.24	n.s.	6.30	0.25	< 0.02
10	0.33	0.23	n.s.	5.66	0.25	< 0.02
11	0.58	0.23	n.s.	4.11	0.24	n.s.
12	11.35	0.21	< 0.0009	16.31	0.21	< 0.00007
13	6.50	0.17	< 0.01	10.80	0.18	< 0.002
14	0.04	0.12	n.s.	15.54	0.14	< 0.0001
15	5.01	0.21	< 0.03	1.10	0.18	n.s.
16	7.59	0.24	< 0.007	8.64	0.25	< 0.004
17	6.66	0.24	< 0.01	13.14	0.23	< 0.0004
18	23.44	0.24	< 0.00001	30.57	0.25	< 0.00001
19	19.72	0.25	< 0.00001	9.42	0.24	< 0.002
20	3.83	0.18	n.s.	7.44	0.18	< 0.007
21	17.30	0.12	< 0.00004	21.13	0.14	< 0.00001
22	0.14	0.15	n.s	1.37	0.18	n.s.
overall	5.19	0.25	< 0.024	8.42	0.25	< 0.004

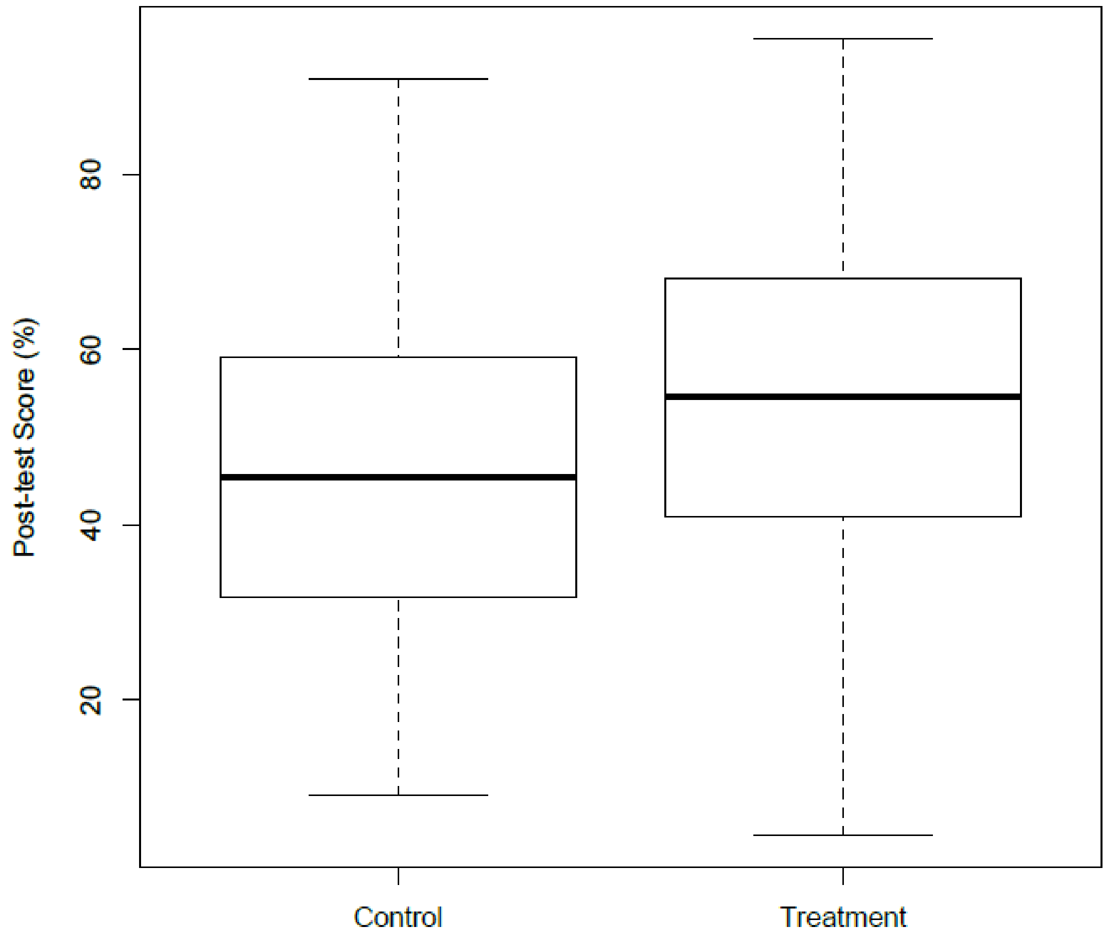


Figure 2   Posttest Scores Distribution Split by Treatment

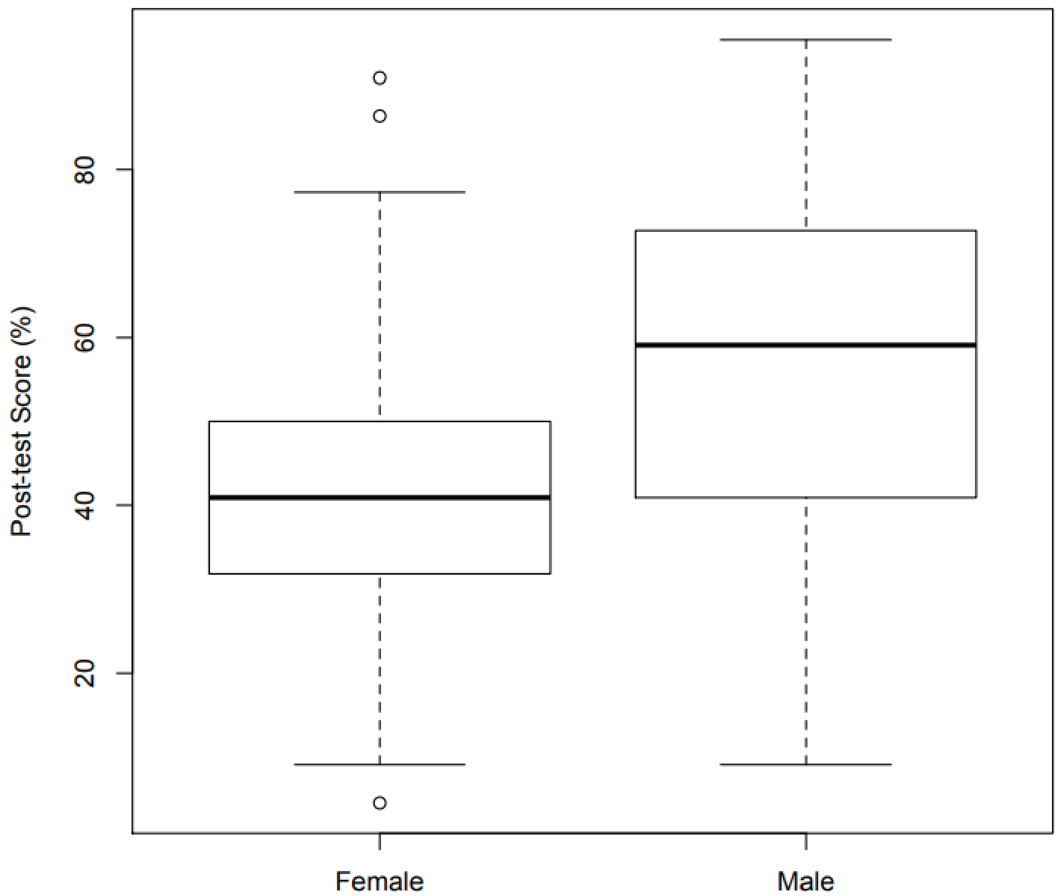


Figure 3 Posttest Scores Distribution Split by Gender for the Whole Sample

CHAPTER SIX: CONCLUSION

1. DISCUSSION

Four research questions were addressed by this investigation:

Question #1: What are the main misconceptions about basic principles in chemistry that CEGEP science students bring from their high-school chemistry courses?

Question #2: Are instructional strategies that foster student interaction more effective than traditional approaches to promote conceptual gains?

Question #3: What factors play a role in acquiring knowledge in introductory college chemistry courses?

Question #4: What is the validity of the CCI with the local population?

1.1 The Main Misconceptions

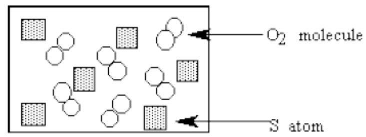
This study was conducted to identify the chemistry misconceptions held by incoming CEGEP students and analyze the effect of instruction in restructuring these misconceptions during their first college chemistry course. Since the majority of Quebec high-school students are taught in French, the study aimed to test the hypothesis that, during the adjustment period to an English college, their language of instruction in high school is a contributing factor to the understanding of basic chemistry concepts and notions. The core hypothesis was that students who learned chemistry in English high schools would perform better because they have an advantage compared to those taught in French.

The pretest results indicate that most students know the fundamental principle that mass-matter is conserved in both physical and chemical processes. However, the number of correct answers is higher (in the 60-80% range) in questions 4, 7, 8, 12, and 13, which deal with recalling the principle. The percentage of correct answers decreased significantly (in the 35-42% range) in questions 1, 10, 11, and 18, which require the association of phenomenological representation with the particulate model for matter. This pattern illustrates novices' difficulties associated with the use of multiple levels of representation, as previously reported in the research literature (Barke, Hazari, & Yitbarek, 2009; Chandrasegaran, Treagust, & Mocerino, 2009; Gilbert & Treagust, 2009; Rappoport & Ashkenazi, 2008; Talanquer, 2011; Treagust, Chittleborough, & Mamiala, 2003).

The concept of phase change appears in four items (questions 2, 3, 6, 10) and is the second most frequent topic of the CCI. In all these items, correct answers in the pretest were in the 37-48% range, which indicate that most students hold misconceptions about this basic phenomenon. Studies have shown that creating a mental image for the phase change representations is a complex task for young learners (Johnson, 2005; Tyter & Vaughan, 2007) since it requires the notion of particles to portray matter (Kahveci, 2013). It has been suggested that one of the possible causes for this result is the fact that instruction does not offer the tools for conceptual understanding since students tend to learn chemistry as propositions and algorithms (Talanquer, 2012; van Berkel, Pilot, & Bulte, 2009). Weaver (2009) pointed out that a concept is also unlikely to be intelligible to students if it lies far outside their zone of proximal development, ZPD (Cracolice, 2005; DelRio & Álvarez, 2007).

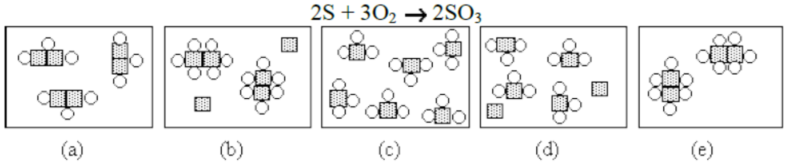
Considering the entire CCI, questions 5, 14, and 22 had the lowest percentage of correct answers in the pretest: 13, 14, and 19% respectively. Although the concepts covered in these questions are distinct, students need to have a good grasp of the particulate nature of matter to apply it to either stoichiometry, mole, or macro vs microscopic properties. In question 5, shown below, both the ratio of reactants and the balanced equation are provided. Applying basic stoichiometry principles enable students to predict the outcome of the reaction.

5. The diagram represents a mixture of S atoms and O_2 molecules in a closed container.



Which diagram shows the results after the mixture reacts as completely as possible according to the equation:

$$2S + 3O_2 \rightarrow 2SO_3$$



The distribution of answers for question 5, Figure 4, indicates that the majority of students failed to take into account the ratio of reactants (answers a, c, and e). The correct answer, (d), was chosen by only 13% in the pretest and 19% in the posttest, which reflects students' struggle to navigate between the symbolic level encoded in the reaction equation (Taber, 2009) and the representation of the particulate nature of matter displayed in the diagram. As underlined by Gabel (2005), students do not fully understand a concept unless they understand it on all three levels and are able to navigate between their multiple representations.

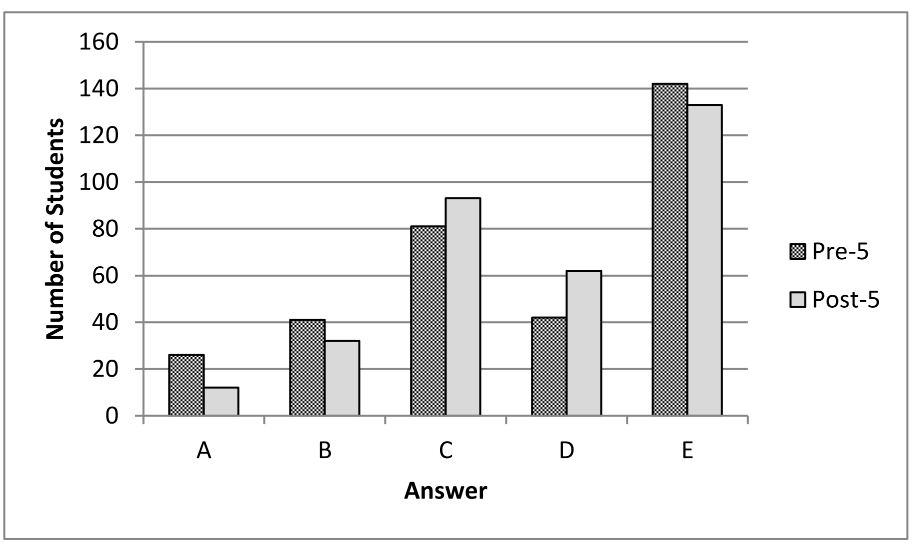


Figure 4 Distribution of Answers for Question 5

Question 14 explores the concept of mole and the scale of atomic size, and it is linked to particulate model of matter. The majority (pre: 78%, post: 80%) chose answer (d), whereas the correct answer, (c), was chosen by only 14% in the pretest and 17% in the posttest.

14. What is the approximate number of carbon atoms it would take placed next to each other to make a line that would cross this dot: ▪

a. 4
b. 200
c. 30,000,000
d. 6.02×10^{23}

Question 22 is the only CCI item that evaluates the difference between macro and microscopic properties of matter. The correct answer, (c), was chosen by only 19% in the pretest and 23% in the posttest.

22. Following is a list of properties of a sample of solid sulfur:

i. Brittle, crystalline solid.
ii. Melting point of 113°C.
iii. Density of 2.1 g/cm^3.
iv. Combines with oxygen to form sulfur dioxide

Which, if any, of these properties would be the same for one single atom of sulfur obtained from the sample?

a. i and ii only.
b. iii and iv only.
c. iv only.
d. All of these properties would be the same.
e. None of these properties would be the same.

The distribution of answers for question 22, Figure 5, indicates that students attributed macroscopic properties, such as density and melting point, to atoms and molecules by assuming the continuity of matter, a prevalent misconception that has been reported in the literature (Kahveci, 2013; Talanquer, 2006).

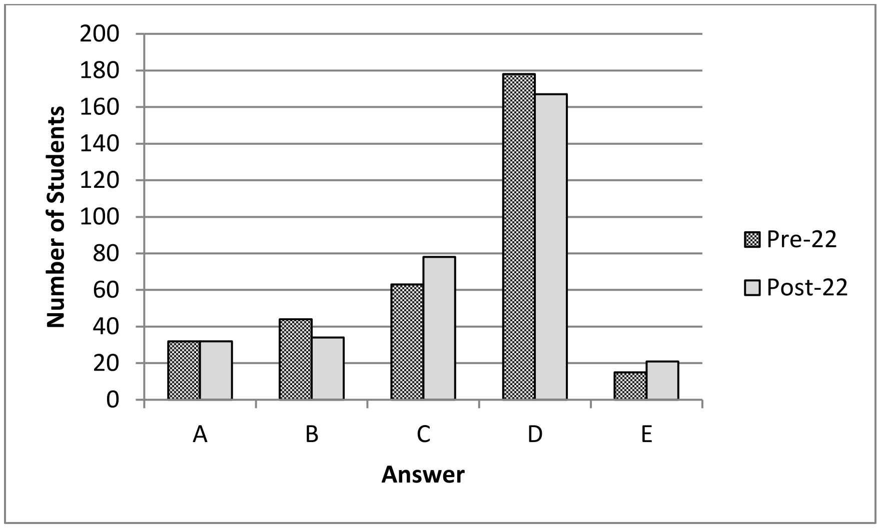


Figure 5 Distribution of Answers for Question 22

As outlined by Kalman (2008), more than 50% of the students entering science and engineering courses in post-secondary institutions do not possess the level of intellectual development required to apply principles to examples in different contexts, a feature that might explain why most students are capable of stating the concept but find it difficult to apply it within the context of counterintuitive chemical models. The results of the current study indicate that incoming CEGEP students hold misconceptions similar to those identified in previous investigations conducted with first-year undergraduate students in the United States by Mulford and Robinson (2002) and Barbera (2013), which have sample sizes of 928 and 3025 students, respectively. In all investigations, the overall gain seems modest taking into account that all these concepts are part of the high-school curriculum. Figure 6 shows the distribution of grades for the pre- and posttest conducted in this study.

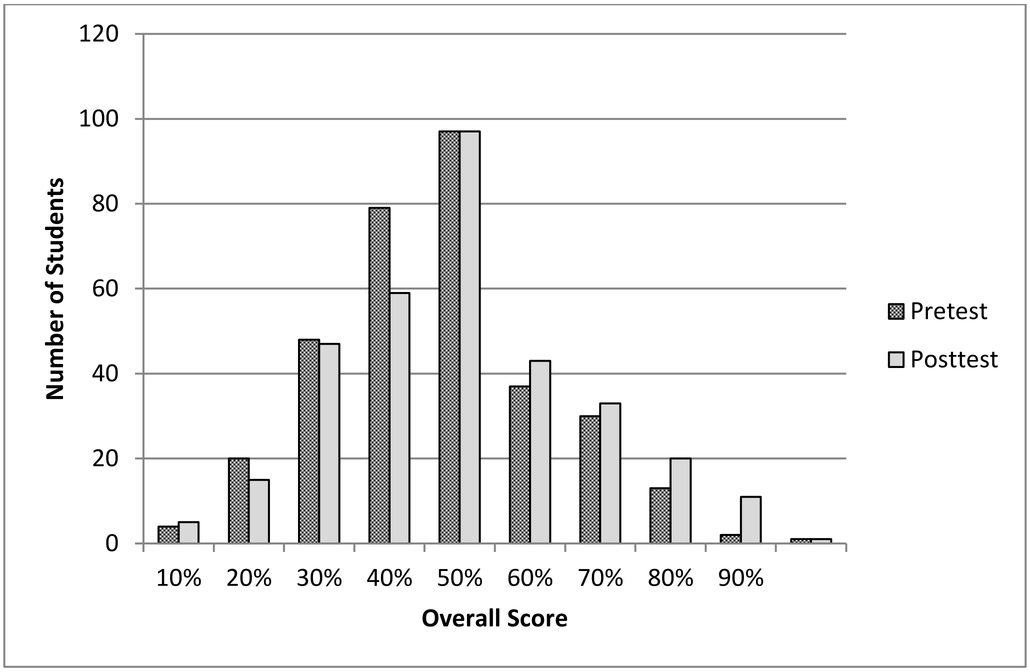


Figure 6 Overall Scores for Pre- and Posttest (N=332)

The comparison between pretests and posttest percentages for each item in three independent studies can be seen in Table 7. It is noteworthy that questions 5, 14, 21 and 22 show the lowest percentages in the whole set for the three independent reported investigations. This is an illustration of the difficulties that learners encounter to associate the particulate model of matter with chemical and physical properties displayed in laboratory experiments. The fact that, regardless of the instructional strategies employed, all samples displayed a similar pattern might be an indication that students at this age do not possess the intellectual maturity to fully understand these abstract models (Cracolice, 2005; Felder & Brent, 2004; Herron, 1975; Kahveci, 2013; Taber, 2005).

Table 7
Pretest and Posttest Percentage Values for Each Item on the CCI

Item	Correct Responses, %					
	This Work (N=332)		Barbera (2013) (N = 3025)		Mulford & Robinson (2002) (N = 928)	
	Pretest	Posttest	Pretest	Posttest	Prestest	Posttest
1	41	44	40	42	37	34
2	41	39	36	45	40	47
3	44	45	54	64	67	72
4	59	63	70	72	73	74
5*	**13**	**19**	**12**	**25**	**11**	**21**
6	48	55	48	52	39	45
7	85	86	87	91	89	92
8	81	86	88	91	88	91
9**	**40**	**53**	**30**	**36**	**28**	**30**
10	37	45	34	36	36	44
11	36	40	33	36	35	42
12	70	71	68	73	69	74
13	78	77	70	75	71	75
14*	**14**	**17**	**23**	**22**	**25**	**32**
15	71	77	66	73	77	79
16	38	45	33	44	33	38
17	40	35	32	37	29	34
18	41	42	50	55	50	54
19	54	58	67	72	61	66
20	24	23	25	25	32	34
21*	**14**	**16**	**14**	**15**	**25**	**26**
22*	**19**	**23**	**22**	**23**	**19**	**25**

* Questions 5, 14, 21 and 22 have the lowest scores in all investigations

** In comparison with previous studies, scores for question #9 are higher for this study, but lower for question 14

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1.2 Student Interaction vs. Traditional Approaches

The second research question explores the connections between conceptual gains and the type of instructional strategies employed. Except for treatment group 15, all cohorts shown in this study were taught in regular classrooms with traditional teacher-centered, lecture-based approaches. Group 15 was taught in an active-learning classroom where students were exposed to computer-generated visual aids from the collection available on the website of Phet Interactive Simulations at the University of Colorado at Boulder (https://phet.colorado.edu/). The animations fostered discussions among students about the different models used to portray the particulate nature of matter by illustrating that, despite their seemly realistic appearance, models are approximations of a reality that cannot be known absolutely (Coll, France, & Taylor, 2005; Coll, 2006). Akaygun and Jones (2013) argued that dynamic visualizations are often an efficient tool to help students restructure their misconceptions, and several researchers have indicated that, despite their intrinsic limitations, computer-generated visual aids have positive effects in student reasoning about chemical phenomena (Geelan & Fan, 2014; Miorelli, Caster, & Eberhart, 2017; Russel & Kozma, 2005; Scalco, Talanquer, Kiill, & Cordeiro, 2018; Tang & Abraham, 2016; Yezierski & Birk, 2006).

As shown in Table 5, the treatment, Group 15, had the highest normalized learning gain, 12.1%, in the sample whose average normalized gain was 6.1%. However, two other groups that were exposed to traditional teacher-centered, lecture-based approaches exhibited comparable gains (10.4 and 9.5%). The results of this work do not indicate a strong correlation between the treatment and the normalized gains measured with the CCI, as seen in Figure 2. This means that the observed differences might result from a complex combination of multiple factors that are not accounted for in the research design of this investigation such as the students' approaches to learn in response to the teaching style (Bretz, 2005; Bunce, 2009; Zusho, Pintrich, & Coppola, 2003).

A comprehensive study published by Stains et al. (2018) showed that, even in flexible classroom layouts, lectures are still by large the main instructional strategy employed in undergraduate STEM classes. To reverse this trend, the authors underlined the necessity of promoting practices that promote student interaction throughout the undergraduate STEM curriculum such as those reported in this study. The indication that classroom practices based on computer simulations might be beneficial for enhancing conceptual learning deserves further investigation. Despite the lack of strong correlation between instruction and conceptual gain, the preliminary results of this investigation are aligned with a large body of evidence that supports that, compared to traditional approaches, instructional strategies that foster student interaction are more effective to promote learning (Drane, Micari, & Light, 2014; Freeman, et al., 2014; Kalman, Milner-Bolotin, & Antimirova, 2010; Mazur, 1997; Mazur, 2005; Parkinson, 2009; Scott, Gray, & Yates, 2013, Von Korff, et al., 2016).

1.3 Factors that Play a Role in Acquiring Knowledge

The third research question is based on the assumption that the language of instruction in high school plays a role in the way students construct meaning in introductory chemistry courses in an Anglophone CEGEP. This work did not find a statistically significant correlation between student achievement and language of instruction. However, the results showed a statistically significant correlation between achievement and gender that is indicative of a gender gap for which males score higher than females. Although gender gaps of similar nature have been reported in studies using the Force Concept Inventory (Karim, Maries, & Singh, 2018; Lorenzo, Crouch, & Mazur, 2006), the current investigation is the first to detect this feature by using the Chemistry Concept Inventory.

There are multiple published studies that suggest an existence of gender gaps in students' achievement in chemistry. Analyzing the gender differences in both cognitive and noncognitive factors associated with achievement in Organic

Chemistry, Turner and Lindsay (2003) found a better correlation between females' achievement and selected cognitive variables, especially spatial visualization, a skill in which they are outperformed by males. Other studies (Coleman & Gotch, 1998; Yezierski & Birk, 2006) reported similar trends in gender-related differences in spatial abilities and imagery. In a study conducted by Shibley Jr., Milakofsky, Bender, and Patterson (2003), a group of students took the same course seventeen years apart. The results indicate a complex pattern in which the types of gender differences varied over time with the emergence of a gap in the area of imagery for which males scored higher than females. Controversy still streams from this topic since other studies claim that the differences that exist in spatial ability were not large enough to explain the differences in science achievement (Scantlebury & Baker, 2007). Yezierski and Birk (2006) showed that animations are more helpful to females and can be effectively used to eliminate misconceptions about the particulate nature of matter. Further investigation is required to elucidate the causes of the apparent gender differences indicated by the preliminary results of this work.

1.4 The Validity of the CCI with the Local Population

The results corroborate the validity of the CCI with the local population. Table 7 compares the trends observed in this study with those reported extensively for American undergraduate students in two investigations conducted independently by Mulford and Robinson (2002) and Barbera (2013) with N=928 and 3025, respectively. The types of identified misconceptions and the magnitude of the normalized gains reported by the authors align with those found in this study, which indicates the validity of the CCI as a tool to analyze conceptual learning under the specific characteristics of Quebec's CEGEP system.

2. LIMITATIONS AND FUTURE RESEARCH

Using Mulford and Robinson's CCI as the main instrument of this study offered the opportunity to compare our results with those previously reported in the literature (Barbera, 2013; Mulford & Robinson, 2002). However, there are intrinsic limitations when using a single multiple-choice instrument to assess students' understanding because the answers might reflect spontaneous intuitions rather than their latent knowledge (Talanquer, 2017). To determine their conceptual understanding, several studies have pointed out the necessity of creating upgraded instruments to access students' train of thought. Alternatives commonly reported in the literature include two-tier multiple-choice question for all items (Birk & Kurtz, 1999), a confidence scale added to items (Brandriet & Bretz, 2014), interviews (Bretz & Mayo, 2018; Duis, 2011; Kruse & Roehrig, 2005; Schwartz & Barbera, 2014; Yan & Talanquer, 2015), and open-ended drawing tool (Barke, Hazari, & Yitbarek, 2009; Cooper, Williams, & Underwood, 2015; Nyachwaya, et al., 2011).

Although the CCI offers the opportunity to compare our results with those previously published, there are items, such as solutions and equilibrium, for which instruction has no effect in observed gains since they are not covered in the introductory chemistry course. On the other hand, Mulford and Robinson's CCI does not assess misconceptions on chemical bonding, an important topic in introductory chemistry courses and for which several types of misconceptions have been reported (Birk & Kurtz, 1999; Hilton & Nichols, 2011; Luxford & Bretz, 2014; Nicoll, 2001; Othman, Treagust, & Chandrasegaran, 2008; Vrabec & Proksa, 2016). For these reasons, developing a concept inventory tailored for this course might be beneficial in future investigations even though developing a new inventory would require a tremendous amount of work (Hamouda, Edwards, Elmongui, Ernst, & Shaffer, 2017; Prince, Vigeant, & Nottis, 2012; Taylor, et al., 2017).

3. IMPLICATIONS

The literature in physics pedagogy illustrates the benefits of the repeated use of concept inventories such as the FCI, which has become a standard in comparative studies conducted in different institutions and countries (Caballero, et al., 2012; Scott, Gray, & Yates, 2013; Von Korff, et al., 2016). Physics teachers have become aware of the intrinsic limitations of traditional teaching strategies to acquire meaningful expert-like conceptual learning (Bani-Salameh, 2017; Kalman, Milner-Bolotin, & Antimirova, 2010). This eye-opening experience has motivated them to search for alternative teaching methods to improve student learning (Karim, Maries, & Singh, 2018; Mazur, 2005).

This work is an exploratory study designed to use and validate the CCI as a tool to analyze students' misconception in introductory college chemistry in Quebec. The size of the sample is large enough for drawing preliminary inferences on correlations, and the findings can be used as guidelines for future investigations. The results of this study are relevant to educators interested in conceptual learning, curriculum development, and assessment. It is noteworthy mentioning that in its first trial in Fall 2015, only two teachers participated in the study, and the sample had only 64 students. When shown the poor results of the students in the first trial, the members of the Vanier College Chemistry Department were shocked but also curious to see if the same pattern would be observed in their classes. The whole department agreed to participate in the second trial in Fall 2016, which gave a sample of 332 students taught by 11 teachers. The results of this study are currently being used in pedagogical discussions among the department members to improve the students' learning experiences.

When combined with the data from the extensive research conducted in the area of conceptual change in chemistry, it is possible to identify common patterns of student thinking in different contexts and levels of instruction (Kahveci, 2013). This study indicates that concepts dealing with the microscopic scale and size of atoms, the distinction between the physical and chemical properties of aggregate matter compared to the properties of its molecular constituents, as well as the energy changes in the formation and breaking of chemical bonds are among the most challenging concepts detected with the CCI. As outlined by Talanquer and Pollard (2010), by connecting research and practice, the findings of these studies can guide the development of a reform-based curriculum that reflects a genuine interest in elucidating the process used by both novices and experts to make sense of chemical phenomena.

It has been pointed out that understanding chemistry requires a conceptual framework that is far more complex than the ability to correlate symbolic and iconic signs with real objects and particulate visualization, but rather it requires the ability to "translate within and across knowledge types, scales, dimensions (structure, energy, time), and approaches" (Talanquer, 2011, p. 193). Although the recognition of such a complex reality is beyond the level of intellectual development of the majority of first-year college students, it is a powerful idea to guide the development of curriculum and classroom practices to help students learn more effectively (Claesgens, Scalise, Wilson, & Stacy, 2008; Levy & Wilensky, 2009; Luxford & Holme, 2015). Mapping the conceptual landscape of incoming college students is a crucial step in the crafting of lesson plans that engage them in the transfer of key concepts and ideas (Atkins, 2010; Cooper, Posey, & Underwood, 2017; Talanquer, 2016) to new settings. Exposing learners to instructional strategies that require them to "think like a chemist" (Talanquer & Pollard, 2010) helps them consolidate a coherent and sophisticated conceptual understanding by which they are constantly challenged to look at problems from multiple perspectives and representations while selecting an appropriate model in each specific context.

The results of this exploratory investigation represent a major step in the study of conceptual learning in introductory college chemistry courses in Quebec. The study confirms the validity of the CCI with the local population and opens the door for its use across the reseau to gather more data that can be used to identify the shortcomings of the instructional strategies that are currently employed. In the long term, Chemistry teachers would have access to useful information that would enable them to craft lessons that improve their students' conceptual learning within the constraints of the CEGEP Science curriculum.

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APPENDIX A

HANDOUTS FOR COMPUTER SIMULATIONS

Phet Simulation: States of Matter

https://phet.colorado.edu/en/simulation/states-of-matter

Written by T. Loeblein for the Phet website

Learning Goals

Students will be able to describe matter in terms of particle motion. The description should include

- Diagrams to support the description.
- How the particle mass and temperature affect the image.
- How the size and speed of gas particles relate to everyday objects
- What are the differences and similarities between solid, liquid and gas particle motion

1. Open Gas Properties and then use the pump to put a little gas into the box.
   a. Observe gas particles' behavior.
   b. Pump in some lighter particles and talk about the similarities and differences that you see between heavy and light particles.
   c. Use the simulation to see how changing the temperature affects the behavior of the gas particles.
   d. Write a description for a gas based on your observations; include diagrams to help with your description.

2. How fast do you think the air particles in this room are moving compared to a car going about 22m/s? Put your answer is in the form, "a molecule travels ___ as fast as a car"

3. Using the simulation, test your idea from question 2 and give evidence to support or revise your thoughts. For evidence, include how you used the simulation to collect data, and any calculations.

4. Open States of Matter; use the simulation to determine how well liquids and solids match your description of gas particles.

5. Write a paragraph that explains the differences and similarities between solid, liquid and gas particle motion; include drawings to help with your explanations.

Phet Simulation: The Photoelectric Effect

Adapted from the guidelines written by D. Baird and P. G. Hewitt for the Phet website.

Learning Goals

To be able to explain how the photoelectric effect experiment works

To be able to explain why a photon model of light is necessary to explain the results

To be able to relate the wavelength of light to the work function of the metal.

The photoelectric effect is one of the key experiments that supported early quantum theory. Light, prior to the early 20th century, was conceptualized as a wave phenomenon. This idea is corroborated by experimental observations—for instance, light is bendable when passed through a lens, and light that passes through two slits creates an interference pattern, which can be rationalized by assuming its wave character. The energy of a wave is directly proportional to its amplitude, so a light wave of a certain frequency should be able to have any value for its energy as long as there is a bright enough light source.

However, when red light was shone on a metal surface, no electrons were ejected even when the brightest red light sources were used. On the other hand, when blue light was shone on the same metal surface, electrons were ejected even when the source of light was weak (and brighter blue lights ejected *more* electrons). This puzzle was nonsensical when light was conceived of as a wave. How could this be? The energy did not seem to depend on the amount of light hitting the metal but instead on the frequency of the light that hit the metal.

Planck put us on the path leading out of this thicket of confusion when he theorized that light and other forms of energy come in discrete “packets.” Light, in this theory, is considered as composed of particles, which we now call **photons**. The photoelectric effect was explained by Einstein when he conjectured that Planck’s photons were causing the electrons to be ejected as long as these striking photons had each more than a certain amount of energy. Einstein’s ideas gave further support to the theory that light energy is in reality not continuous with infinitely small increments of change (as with a wave) but is in fact “chunky.”

Today’s class involves a simulation of the photoelectric effect. You will be checking various metals for the point at which they begin to shed electrons, based on a specific **threshold frequency**—the exact point when the photons have enough energy to knock the electrons loose. This energy is called the **work function (W)** for the metal. Metals hold on to their electrons more strongly or weakly due to their atomic structure, so the work function for various metals varies. The formula for calculating W is as follows:

$$h\nu = E_k + W$$

Where

- h is Planck's constant (6.6262×10^{-34} J·s)
- ν is the frequency of the light (in Hz)
- E_k is the kinetic energy of the ejected electron ($E_k = \frac{1}{2} mv^2$)
- W is the work function (in joules)

The kinetic energy of the electron refers to its actual movement once ejected. E_k can effectively be ignored if we just reach the amount of energy to loosen the electron but not get it moving (E_k in these circumstances will essentially have a value of zero). You will be trying to achieve the lowest possible speed for the electrons you eject from the virtual metal surface.

The work function (W) can be calculated in Joules and then converted to electron-Volt (1 eV = 1.60×10^{-19} J).

The Photoelectric Effect Simulation

1. Go to the link http://phet.colorado.edu/en/simulation/photoelectric
2. Click on Run Now!
3. Keep battery voltage at 0.00 V. Turn light intensity up to 70%. You will be testing the three metals (Na, Ca, and Zn). Metals can be selected in *Target*.
4. Adjust the wavelength to a value which just allows electrons to leave the surface at the lowest possible speed.
5. Record the maximum wavelength and the corresponding frequency in the provided table.

Metal	**Maximum wavelength (nm) for ejecting electrons**	**Frequency (Hz)**
Calcium		
Zinc		
Sodium		

6. Assume that E_k is zero to calculate the work function both in joules and in electron volt for each metal. Place the metals in order of **<u>increasing value</u>** of work function in the table below. Convert the work function to electron-volt. (1 e.V. = 1.60×10^{-19} J).

Metal	**Work function (J)**	**Work function (eV)**

7. Select the following parameters (Sodium, 350 nm, 50% intensity, 1.00 V). Turn the light intensity up and down. Analyze the changes observed. Enable the graph of current *vs.* light intensity. Rationalize the observed pattern with reference to the principles of the quantum theory.

Influence of light intensity on electric current	

8. Select the following parameters (Sodium, 350 nm, 50% intensity, 1.00 V). Slowly move the slider that changes wavelength back and forth. Analyze the changes observed. Enable the graph of electron energy *vs.* light frequency. Rationalize the observed pattern with reference to the principles of the quantum theory.

Influence of light frequency on electric current	

9. Select the following parameters (Sodium, 350 nm, 50% intensity, 0.00 V). Slowly move the slider that changes the battery voltage back and forth. Analyze the changes observed. Enable the graph of current *vs.* battery voltage. Rationalize the observed pattern with reference to the principles of the quantum theory.

Influence of battery voltage on electric current	

Phet Simulation: Models of the Hydrogen Atom

Written for the Phet website by T. Loeblein based on the handout by A. Webb

Learning objectives

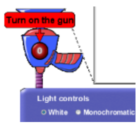
Students will be able to

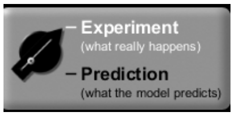
connect the importance of inference from experimental data.

explain the concept of energy absorption and energy emission.

identify the significance of only specific wavelengths of light being absorbed or emitted.

Procedure and analysis

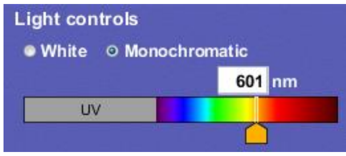
Turn the light beam "on." 

and "Experiment" hi-lighted white. Observe 

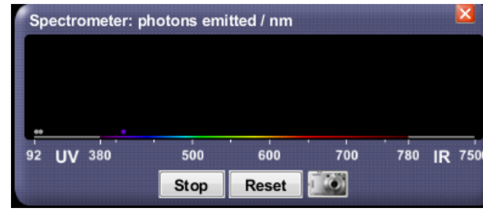
what is happening while photons are being sent through a hydrogen atom. Describe and draw your observations:

When determining how an atom works, scientists witnessed something similar to what you are witnessing now. They then deduced how the atom must be organized. What do you think is making the photons deflect? What do you observe about how many or what color photons are defected?

Change the Light control from "White" to "Monochromatic". What does "monochromatic" mean? Make sure to try moving the slider. What is similar and what is different about the photon behavior?



Click the “show spectrometer” box. 

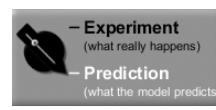


a. Change the colors of the photons to the suggested colors let the simulation run for several minutes then, record observations:

Color	Observation
UV	
Purple	
Green	

b. What is the spectrometer box keeping track of?

Understanding different Models of the Hydrogen Atom:



Now that you’ve theorized about what is happening to the photons of energy, hi-light the “Prediction” button and observe other scientist’s theories about the atom. When you are working on this section, make comparisons by

Using a wavelength of 97 nm and white light.

Use “experiment” and “predictions”.

Use the spectrometer and observations about photons

Complete the chart below by comparing the 6 models with the experiment (what is really happening) and try to explain why the model does/does not explain the experimental observations.

Atomic Model	Observations	How does it support or not support the experiment?
Billiard Ball		
Plum Pudding		
Classical Solar System		
Bohr		
De Broglie		
Schrödinger		

With the Bohr's model selected, click the "Show electron energy level diagram." Using the Electron Energy Level Diagram and the spectrometer, describe what is happening to hydrogen's one electron.

In the help menu, click on transitions. Enter the first 5 wavelengths into the wavelength box and observe what happens to the electron. Does this support your ideas in #2? If not, readjust your statement to explain you new ideas about the behavior of the electron.

Now enter wavelengths that are not listed. What do you observe? Does this support your ideas? If not, readjust your statement to explain the new behavior of the electron.

APPENDIX B

CONSENT FORM FOR STUDENT PARTICIPATION

Consent Form
Using Peer Instruction to Enhance Conceptual Learning in First-Year Cegep Chemistry
Fall 2016

Researchers

Dr. Jailson Farias de Lima
Chemistry Department, Vanier College

Dr. Elizabeth Charles (Advisor), Dawson College

Description of the Research

This study aims to identify misconceptions in chemistry held by first-semester CEGEP students and to analyze the role of peer instruction in restructuring these misconceptions. The research involves collecting products from classroom activities and assignments. Specifically, we are asking your permission for the following: (1) a survey with personal information (age, gender, mother tongue, language of instruction in high school); (2) answering two multiple-choice concept tests (22 questions, 30 minutes each) at the beginning and at the end of the course; (3) Copies of relevant assignments and assessments, including quizzes and tests. You are not required to do anything over and above the normal requirements for this course. Specifically, all of these will take place in class, during your regular class time. No specific testing is required to determine eligibility for research participation. Your educational record will not be reviewed, nor will your participation result in missed school or work.

Potential Harms

There are no known harms associated with your participation in this research.

Potential Benefits

If the research shows improved student learning, these results may be used as a guide to design instructional strategies that enhance the quality of instruction by providing more interactive, engaging, and rewarding lessons in future courses you take at Vanier.

Confidentiality

All information collected for the purpose of this research will be kept strictly confidential. No names or any other identification will be used in any publication that may result out of this study. Your data will be assigned a pseudonym or general character type or code. Data collected by this project may be published, used with other data sets, and/or used in a future study, or series of studies, on the research topic. The data will be destroyed on or before the date, which is the earlier of ten (10) years from the commencement of the study or seven (7) years from the publication of results. That said, further study on this topic may be conducted as part of a larger program of research, in which case data from this study may be used with other data sets.

Participation

Participation in research must be voluntary. If you choose not to participate, you will continue to have access to quality education. If you choose to participate and later decide to change your mind, you can say no and stop the research at any time. Again, you will continue to have access to quality education.

Statement of Consent

I certify that I have read the above information, understand the risks, benefits, responsibilities, and conditions of participation as outlined in this document, and freely consent to participate in the project Using Peer Instruction to Enhance Conceptual Learning in First-Year CEGEP Chemistry. I will receive a copy of this consent for my records. I have reviewed the contents of this consent form. I have had the opportunity to ask questions, and my questions were answered to my satisfaction.

□**YES** □**NO**

Name:______________________Signature:_______________ Date: ___________
(in block letters) DD/MM/YYYY

STATEMENT OF PARENTAL/GUARDIAN CONSENT (for participants under the age of **16** years) I certify that I am the legal parent or guardian for ____________________________ (Name) born ______________________________ (Date of Birth). I certify that I have read the above information, understand the risks, benefits, responsibilities and conditions of participation as outlined in this document, and freely consent to ____________________________ 's (Name) participation in the ______ project. Parental/Guardian Name:

APPENDIX C

VANIER COLLEGE RESEARCH ETHICS BOARD APPROVAL

VANIER
CÉGEP · COLLEGE

May 14, 2015

Jailson Farias de Lima
Vanier College

Dear Jailson,

The Vanier College Research Ethics Board has reviewed your research entitled; *Using Peer Instruction to Enhance Conceptual Learning in First-Year CÉGEP Chemistry*, and has granted their certification for your project. The Board has deemed your research low risk and you do not need parental consent for participants less than 18 years of age.

Regards,

Marc Belanger
Chairperson
Research Ethics Board

encl.
nb

VANIER
CÉGEP COLLEGE

VANIER COLLEGE
RESEARCH ETHICS BOARD
RESEARCH CERTIFICATION

This is to certify that the Research Ethics Board of Vanier College has examined the research proposal by

____Jailson Farias de Lima_____
name of applicant(s)

entitled: ____ Using Peer Instruction to Enhance Conceptual Learning in First-Year CÉGEP Chemistry____
title of project

Ethics approval is granted for a period of one year from the date of this approval. After that date, all research must cease unless an application for renewal has been approved. A final report summarizing the findings of the study should be submitted to the Vanier College Research Office within six months of study completion.

RESEARCH ETHICS BOARD MEMBERS

Marc Belanger- Chair

Allen Insleay

James Pan

Toby Moneit

Karen White

May 14, 2015
____
Date

____
Board Chairperson

VANIER
CÉGEP/COLLEGE

May 20, 2016

Jailson Farias de Lima
Vanier College

Dear Jailson,

The Vanier College Research Ethics Board has reviewed your request for an extension for the research entitled; *Using Peer Instruction to Enhance Conceptual Learning in First-Year CÉGEP Chemistry,* and has granted their certification for your project for one more year.

Regards,

Karen White
Chair
Research Ethics Board

encl.
nb

VANIER
CÉGEP/COLLEGE

VANIER COLLEGE
RESEARCH ETHICS BOARD
RESEARCH CERTIFICATION

This is to certify that the Research Ethics Board of Vanier College has examined the research proposal by

____Jailson Farias de Lima_____
name of applicant(s)

entitled: *Using Peer Instruction to Enhance Conceptual Learning in First-Year CÉGEP Chemistry*
title of project

Ethics approval is granted for a period of one year from the date of this certificate. After that date, all research must cease unless an application for renewal has been approved. A final report summarizing the findings of the study should be sent to the Vanier College Research Office within six months of study completion.
Any changes or modifications to approved instruments and/or procedures must be submitted, through a new application, to the Vanier College Research Ethics Board prior to the collection of data.

RESEARCH ETHICS BOARD MEMBERS

Karen White - Chair

Allen Insleay

James Pan

Toby Moneit

Marie-Sophia Grabowiecki

May 20, 2016
Date

Board Chair